



INVESTIGATIONS INTO NEAR INFRARED
SENSITIVE SOLAR CELLS

THESIS

Andrew M. Jones, 1st Lieutenant, USAF
AFIT-ENG-MS-17-M-037

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in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Electrical Engineering

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Abstract

In the solar industry today many new endeavors rely on improving efficiency on existing solar technologies such as silicon and gallium arsenide based solar cells. Other new technologies tend to lean towards cadmium or organic based devices in an attempt to produce more effective, less costly solar devices. While this is good for business and growth, the underlying problem of improving efficiency will not be solved by staying in a low cost box of a handful of choices. This research is focused outside this material box by looking into improving the hybrid multi-junction silicon germanium (HMJ-SiGe) solar cell structure, a germanium based solar cell device. An antimony doped germanium substrate is used in conjunction with germanium telluride, in an approximate 1:1 ratio in order to produce a functional solar cell device. Using standard processing techniques already in use in the commercial industry, samples are created and tested using solar simulator, spectroscopic equipment and standard electronics testing equipment. Layering germanium telluride on top of a doped germanium sample, followed by contacts and an anti-reflective layer of silicon nitride allowed for a functional solar cell producing 103.7mV and 470uA developing a 0.049% efficient device. These results show that a device is feasible, however more research into improving efficiency and lowering costs are required before it can be adapted for use in other device structures.

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Dediti orbabor filio in quaerendo pacem

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Andrew M. Jones

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List of Symbols

E_c conduction band.

E_f fermi-energy level.

E_g band gap energy.

E_v valence band.

I_s saturation current.

V_a applied voltage.

α lattice constant.

ϵ_s permittivity.

λ wavelength of light.

μ_n electron mobility.

μ_p hole mobility.

ν frequency.

c speed of light in vacuum.

h planks constant.

θ angle of incidence.

n index of refraction.

k Boltzmann's constant.

I_{sc} short-circuit current.

J_s saturated current density.

N_a acceptor dopant concentration.

N_d donor dopant concentration.

n_i intrinsic carrier concentration.

q electron charge.

R_s sheet resistance.

T temperature in kelvin.

V_{oc} open-circuit voltage.

List of Acronyms

AFIT	Air Force Institute of Technology
Al	Aluminum
Al ₂ O ₃	Aluminum Oxide
ALD	Atomic Layer Deposition
AM	Air Mass
ARC	Anti-Reflective Coating
Au	Gold
BOE	buffered oxide etchant
Cd	Cadmium
CdTe	Cadmium Telluride
ChG	Chalcogenide
DI	deionized
EDAX	Energy Dispersive X-ray Spectroscopy
EDS	energy dispersive x-ray spectroscopy
GaAs	Gallium Arsenide
Ge	Germanium
GeTe	Germanium Telluride
GeTe	germanium telluride
GST	Germanium Antimony Telluride
HF	Hydrofluoric Acid
HMJT	Hybrid Multi-Junction Tandem
In	Indium

MATLAB	Matrix Laboratory
MEMS	Micro-Electro-Mechanical Systems
N ₂	Nitrogen
NIR	Near-Infrared
PDF	Probability Distribution Function
PECVD	Plasma Enhanced Chemical Vapor Deposition
RTA	Rapid Thermal Anneal
S	Sulfur
Sb	Antimony
Se	Selenium
SEM	Scanning Electron Microscope
Si	Silicon
Si ₃ N ₄	Silicon Nitride
STC	Standard Test Conditions
Te	Tellurium
Ti	Titanium
UV	Ultraviolet
V ₂ O ₅	Vanadium Pentoxide
V _x O _y	Vanadium Oxide

INVESTIGATIONS INTO NEAR INFRARED SENSITIVE SOLAR CELLS

I. Introduction

1.1 Overview

This chapter provides a brief history and discussion of the limitations and importance of the research within. This will inform the reader of the scope of this work as well as the methodology used and provide justification in pursuing this research.

1.2 Photovoltaic History

The beginning of the photovoltaics field is commonly believed to have began in the early 1800's. The exact date of the first observation of the photovoltaic effect is unclear, but this date is adopted based on publications of researchers during this time. The first documented case of observed photovoltaic response occurred with a young French physicist, Alexander Edmond Becquerel. In the year 1839 Becquerel observed that a voltage was created across electrodes suspended in an electrolyte solution when they were exposed to light[1]. Following this, other observations were made by C.E. Smith, W.G. Adams and R.E. Day in which Selenium (Se) increased in conductivity when illuminated [2],[3]. Their research lead to the development of the first specifically designed solar module in 1885 by Charles Edgar Fritts[4]. Fritts applied a layer of Se followed by a thin gold layer on top of a copper plate. With this setup he observed a noticeable current flow when the material was illuminated that would one day "compete with fossil fuel plants"[3]. Unfortunately, this bold statement held little water until very recently, in 2016, in an article published by

Bloomberg magazine stating that solar and fossil fuels are "beginning to compete head-to-head on price and annual investment" [5].

1.3 Objectives

The goal of this research is to develop and understand solar cells created using Antimony (Sb) doped Ge wafers and the Chalcogenide (ChG) GeTe. Once an understanding is established, further investigations into Hybrid Multi-Junction Tandem (HMJT) device concepts will also be analyzed to determine the overall effectiveness of these combination of devices. In order to accomplish this, Matrix Laboratory (MATLAB) modeling and specific changes to processing variables will be investigated.

1.4 Justification

Many research endeavors have taken place regarding solar cell development, yet the majority of materials used in their fabrication remain generally the same. Many advances in both organic and non-organic solar cell production methods have occurred, yet non-organic devices haven't changed significantly. The most commonly used, non-organic, materials to date consist of: Silicon (Si), Cadmium Telluride (CdTe), Gallium Arsenide (GaAs) and blends of the aforementioned materials with Indium (In) and Se[6],[7],[8],[9]. While these have lead to great achievements in the solar field, little effort has been spent on investigating Ge and other ChG materials, other than Cadmium (Cd) based ChGs, for use in photovoltaics.

1.5 Scope

The focus of this work consists of solar cell creation using Ge, Germanium Telluride (GeTe) and other non-conventional photovoltaic materials to create a functioning solar device. Band theory and semiconductor physics will be used in order to predict

and analyze the impact of changes made during processing to the end product. Further investigations into HMJT will then be pursued to determine any improvements into the near infrared region of the solar spectrum using the Ge based solar devices in the HMJT structure.

1.6 Methodology

Using semiconductor physics and basic electrical material properties the produced devices will have operation verified and analyzed. MATLAB scripts will be developed in order to predict results of fabricated devices based on the initial analysis. Once created, samples will be measured using both a solar simulator at Standard Test Conditions (STC) and parameter analyzer in order to characterize junction formation and voltage responses.

II. Background

2.1 Overview

This section provides a brief description and history of concepts used during investigations pursued with this research.

2.2 Energy Band Theory

From the Bohr model of an atom shown in Figure 1 electrons may exist at different energy levels within a materials atomic structure in regions called shells [10]. This description is known to work well for an individual atom, however in a crystal structure an electron is affected not only by its atomic nuclei, but by the nuclei of neighboring atoms within the structure. This problem lead to the development of the Kronig-Penney model of an atom. In this model, each atom in the crystal creates a local potential well that attracts electrons. Because of these potential wells, the path an electron of finite energy takes through the crystal creates a map of the wells within the crystal. In other words, the energy band theory is a way of representing the regions within a crystal that an electron may exist, based on the electron energy levels[11].

Since there are a seemingly infinite number of energies an electron can potentially have, the entire range of energies are lumped into band regions[12]. These two main regions are referred to as simply the conduction (E_c)and valence bands(E_v). The E_v of the crystal is the highest energy region filled with electrons at absolute zero. Likewise, the E_c is the lowest energy level electrons occupy once the temperature of the material begins to deviate from absolute zero [10]. The difference between these two values (E_v & E_c) is the energy band gap (E_g) shown in Figure 2. In an intrinsic (pure) material the midpoint between E_c and E_v is the E_f . E_f is the energy

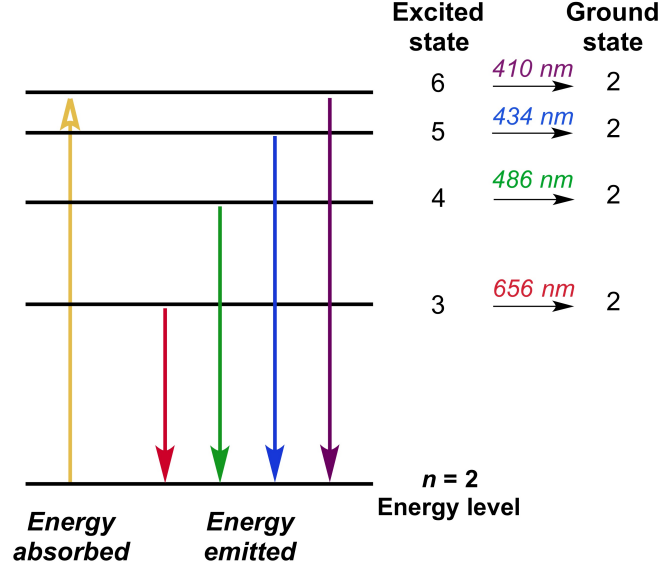


Figure 1. Bohr atomic model of Hydrogen showing the separation of energy levels and energy absorption effects[12].

level at which an electron is equally likely to have energy greater than or equal to E_c or E_v and follows the Probability Distribution Function (PDF) for the Fermi-Dirac Distribution defined as:

$$f(E) = \frac{1}{(1 + \exp[\frac{E-E_f}{kT}])} \quad (1)$$

For an intrinsic material, the likely-hood of an electron being either in the E_c or E_v is 50% because the crystal structure is in a natural equilibrium state. This level can be adjusted through doping similar to that shown in Figure 3. This can make a normally non-conductive material more conductive or an conducting material more insulating and follows Equation (2) [11].

$$\Phi_F = \frac{kT}{q} \ln\left(\frac{N_x}{ni}\right) \quad (2)$$

Where Φ_F is positive or negative for $N_x = N_a$ and N_d respectively.

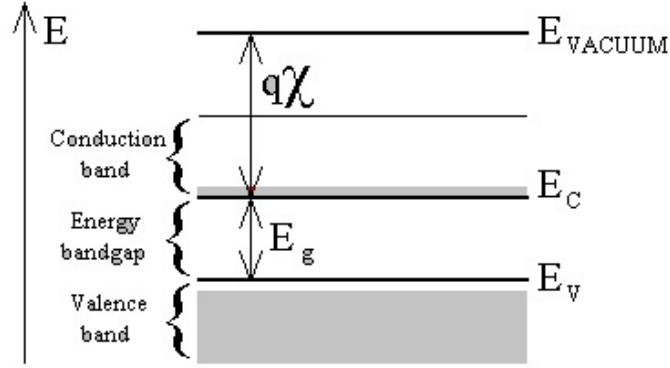


Figure 2. Visual depiction of the energy bands and band gap of a generic material[13].

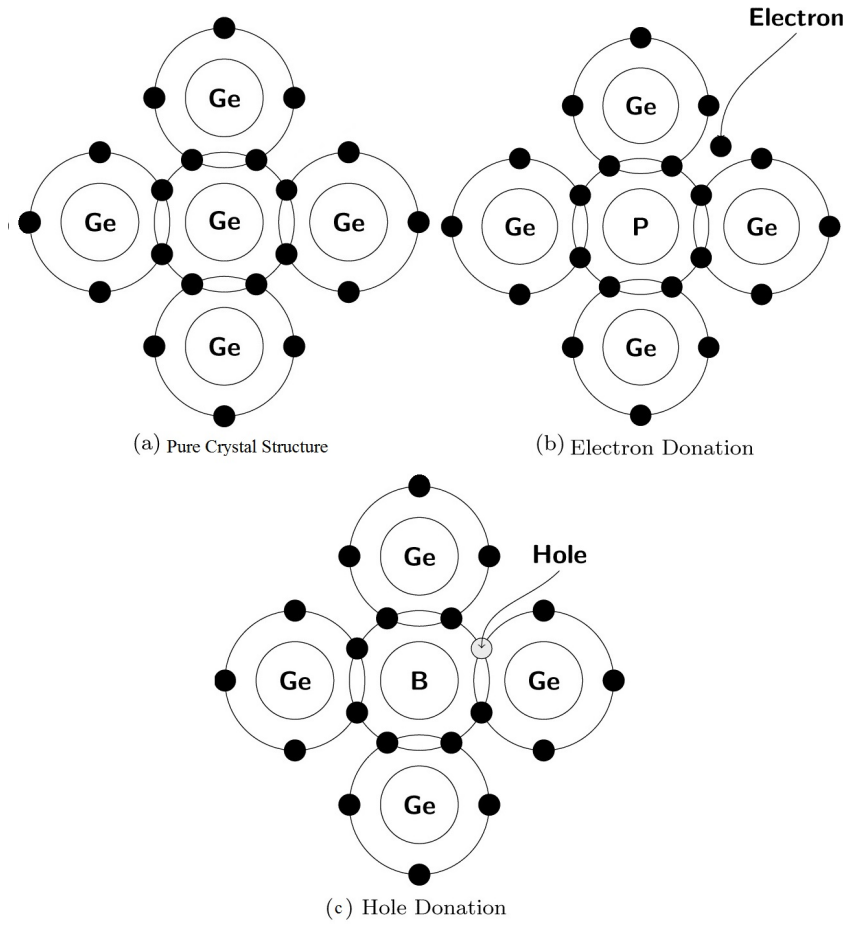


Figure 3. Intrinsic (a), N-Doped(b) and P-Doped(c) germanium crystal structure representation showing ionic bonds formed (or not formed) between elements[13].

2.3 Photoelectric Effect

The photoelectric effect describes the process in which light incident on a material increases the energy of the electrons within the material[12]. These electrons then

make a transition from their relaxed state in the valence band of the material to the conduction band. Here they are free to traverse the material and in the case of electrically conductive materials, be collected for use in electronic devices. This effect was first discovered by Alexandre Becquerel when he observed an increase in current across metal leads immersed in reactive solutions when the leads were illuminated [1]. In 1905 Albert Einstein combined the results of other researchers and produced a mathematical descriptions of the photoelectric effect in which he solved a fundamental flaw in current theories. By proposing that the energy of light (photons) existed in packets of energy, Einstein was able to answer the questions stumping the physics community with the following the formula:

$$E = h\nu = \frac{hc}{\lambda} \quad (3)$$

where E is energy, $h = 6.6261 \times 10^{-34} \frac{m^2 kg}{s}$ is planks constant, $c \approx 3 \times 10^8 \frac{m}{s}$ is relative speed of light in vacuum, ν is the frequency of light in the medium and λ is the wavelength of the incident light[14],[15]. It was then in 1914 when Robert Millikan (1865-1953) *et al.* determined that the wavelength of incident light did indeed dictate the generation of electrons[16]. This discovery not only proved Einstein's theories, but also lead Einsteins' presentation of Nobel Prize in 1922 for the discovery [17]. In addition to this, Millikan *et al.* also observed that the intensity of light directly affected the rate at which electrons were excited[16]. Early physicists were able to prove this effect by placing two electrodes in a vacuum where they observed an increase in current flow between the two charged electrodes only when one was illuminated by light as shown in Figure 4.

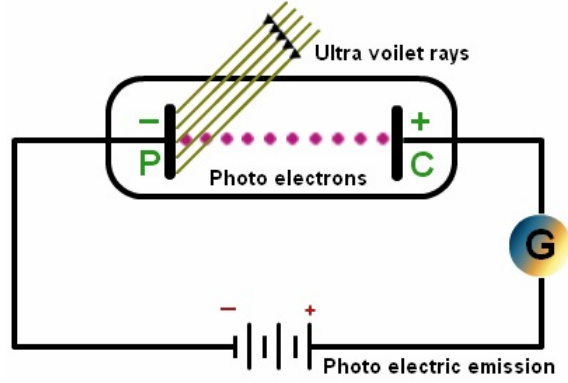


Figure 4. Depiction of the experimental setup used by early physicists to observe the photoelectric effect[12].

2.4 Light Properties

Because of the work of early physicists, fellow physicist James Clerk Maxwell (1831-1879) was able to develop the theory behind what is now termed Maxwells equations [18]. This allowed for the description of light by transverse electric and magnetic fields that travel perpendicular to each other at a particular frequency, λ_0 . In any medium that isn't vacuum this value changes to:

$$\lambda = \frac{\lambda_0}{n} \quad (4)$$

where n is the index of refraction of the medium as determined through testing. This index is described as the ratio of the speed of light in vacuum to speed of light in the medium, which, as mentioned in Section 2.3 has an inverse affect the generation of electrons within a material. It also affects whether or not light will even enter or exit a material at interfaces. This is conveniently described by the law of refraction, also called Snell's law, described in Equation (5) and depicted in Figure 5 [12].

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (5)$$

where n_1 , n_2 , θ_1 and θ_2 are the indexes of refraction and the angles of incidence of light at the transition plane between two mediums.

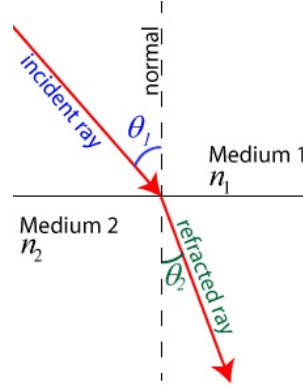


Figure 5. Visual representation of Snell's Law, the law of light refraction[12].

2.4.1 Air Mass.

As it was inferred in Equation (5), the angle of incoming light can have significant impact on the function of a light responsive device, such as a solar cell. Because of this, the position of the sun is very important in dealing with photovoltaic devices. Because of this importance, the concept of Air Mass (AM) was developed to easily describe the atmospheric conditions when describing operating or test conditions of a photovoltaic device. The AM, visually depicted in Figure 6, is the cross sectional area that solar radiation must pass through to get to the measurement point or device. The atmospheric thickness directly over the measurement point is: AM 0 which is radiation in space while AM 1 is radiation with the sun directly over the measurement point, or solar cell [19].

2.5 Semiconductor Material Properties

Semiconductor have varying properties based on their atomic composition that are of particular interest in electronics. Researchers and engineers take advantage

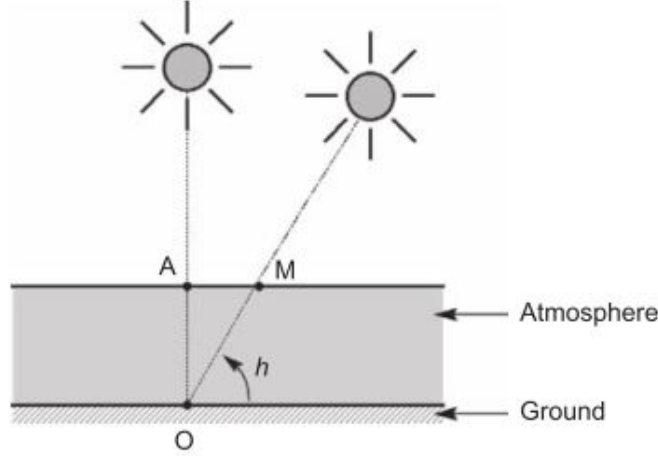


Figure 6. Visual representation of what is meant by air mass in terms of photovoltaics. The points A and M are entry points of a wave of light into the atmosphere, O is the observation point and h is the angle of the source from the observation point with respect to the ground[19].

of these differences to improve device designs and choose the optimal materials for particular applications, such as photovoltaics [20].

2.5.1 Sheet Resistance.

The sheet resistance (R_s) of a material is the measure of resistance between two points on the surface of that material. The typical method to determine sheet resistance is through use of a four-point probe. This test set uses four probes separated by a fixed distance to apply varied voltages and measure currents produced across the surface of the material. From these measurement results, an Ohms-per-square area value for R_s can then be determined using the relationship described in Equation (6) [21]. This value can be converted to an Ohm-cm value by multiplying by the thickness of the material tested. This results in the resistivity (ρ) of the material:

$$R_s = \frac{\rho}{\Delta h} = 4.53 \times \frac{V}{I} \quad (6)$$

which is what is used in semiconductor parameter description equations. In this equation, Δh is the thickness of the material measured, V is the applied voltage and I is the measured current.

2.5.2 Semiconductor Impurities (Doping).

The process of doping a semi-conductor consists of simply replacing substrate atoms with other elements (shown in Figure 3). Since the material properties depend heavily on the overall atomic structure, addition of these impurities changes the physical properties of the material. One such property of interest is the sheet resistance previously mentioned in Section 2.5.1. Using the mobilities (μ_n and μ_p) of the electrons and holes, respectively, within a material, the dopant concentrations can be approximated using:

$$\sigma = \frac{1}{\rho} = q(n\mu_n + p\mu_p) \quad (7)$$

. Where $n \approx N_d$ and $p \approx N_a$, and the assumption is made that the concentration of added impurity greatly outnumbers the natural concentration of the material. This results in more negatively or positively charged (N-type, P-type respectively) materials.

2.6 Solar Radiation

Solar cells are typically characterized in terms of output power as they are power generating devices. Because of this and the fact that the majority of solar radiance has a wavelength of 1400nm and less, shown in Figure 7, the general assumption is that a solar cell will be operating optimally at a wavelength of light of approximately 600nm. Because of this assumption and due to its vast abundance, Si has become the leading material of choice for solar cell fabrication. This trend began in 1956, Gordon

Pearson, Daryl Chapin, and Cal Fuller first used Si to produce a solar cell, achieving a much-improved efficiency, over existing technologies, of 4% and introducing Si as a key material in solar energy production [22]. The relatively low cost and flexibility of Si with doping materials, has kept this trend in place to date. In light of the mechanically stacked or HMJT structure attempting to capture more of the solar spectrum, and current efficiency for a dual junction devices at 29.8%, it appears that more care must be taken at the wavelengths away from 600nm. The regions that this research aims to capitalize on are the regions in which Si appears transparent, the Near-Infrared (NIR) region of light[23]. It is not just the selectivity of Si that drives this wavelength as the key region of scrutiny, but also the source of light in our solar system, the sun. The sun burns at approximately 6000K[24] which, according to black body radiation shown in Figure 7 has quite a lot of energy in a part of its spectrum that is currently being neglected.

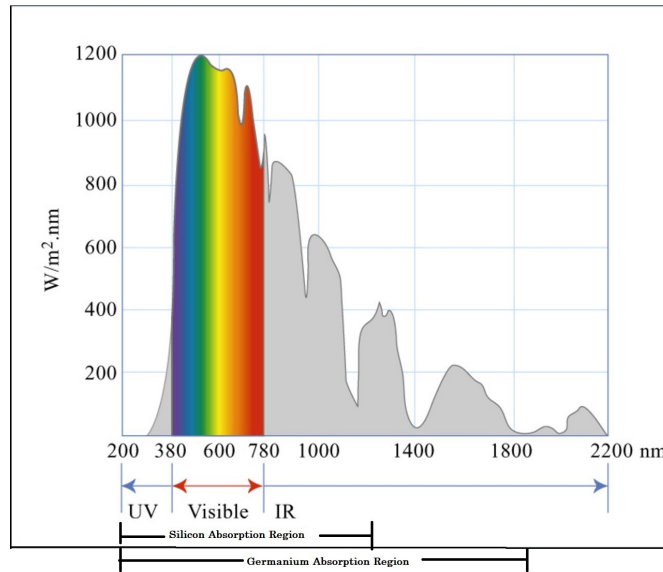


Figure 7. Black body radiation solar spectrum depicting the visible light region and the approximate regions of near infrared and infrared discussed in this work[20].

2.7 The PN Junction Diode

The process of adding an impurity to a crystalline material discussed in Section 2.2 is the basis for forming what is called a PN Junction. Adding elements with more than four valence electrons introduces an excess of electrons in the crystal structure, making it an N-type material. Likewise, adding elements with less than four valence electrons in their outermost shell, causes an overall deficit of electrons, making the crystal P-type. The formation of a PN Junction begins when an N-type material is placed in contact with a P-type material. The joining region is then activated,

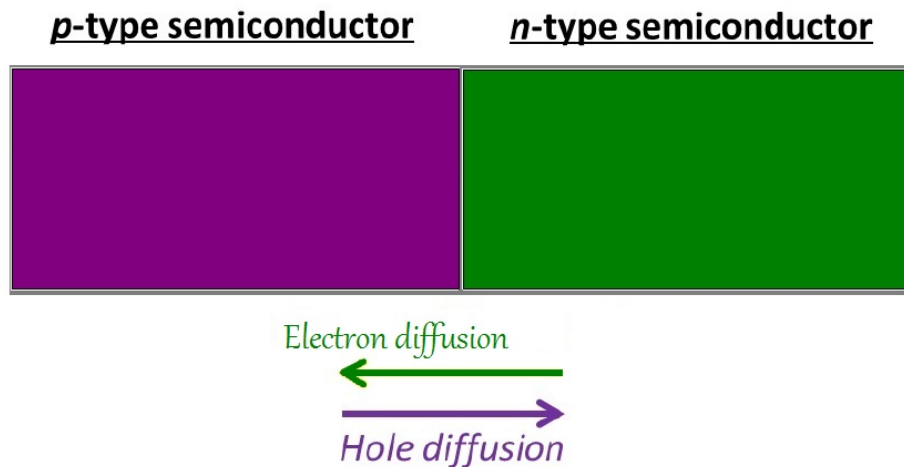


Figure 8. PN junction before activation, each material represented by its net charge[11].

usually by heating the materials, causing electrons from the N-type material to fill in deficiencies in the P-type material and vice versa. This creates a region of ionically bonded atoms across the initial point of contact. As these bonds form, they leave behind neutral regions. As bonds occur, the neutral regions grow in both directions until equilibrium is achieved. The newly created region is called the depleted region of a PN Junction. The depleted region of a PN junction formed of homogeneous materials has a maximum electric field across it based on the concentration of the original N-type and P-type materials. This field can be described using Poisson's

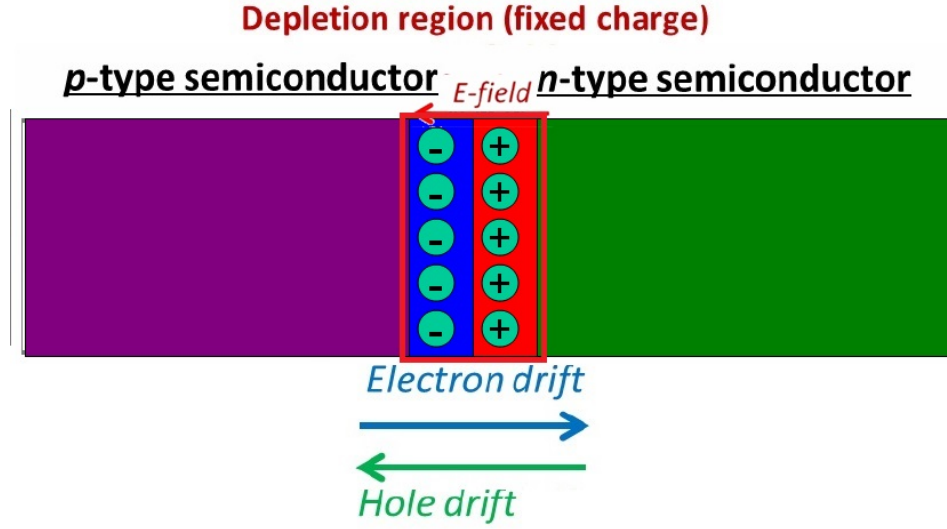


Figure 9. PN junction after activation, showing remaining charge in each material as well as the depleted region formed during activation[11].

equation in terms of the two concentrations, resulting in the equation:

$$\Phi = \Phi_n - \Phi_p = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right) \quad (8)$$

[13]. The actual size of the PN junction, called the depletion width can be found

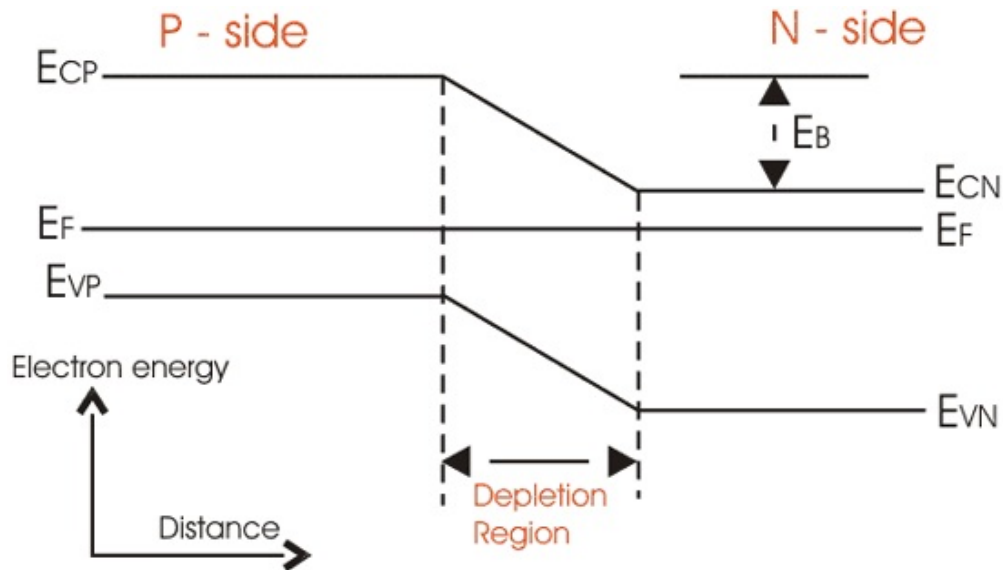


Figure 10. Energy band diagram of an activated PN junction.[11].

from the junction potential and the understanding that all of the E-field is across the depletion width. This results in a total depletion region which is the sum of the depletion widths for the p and n regions, l_{po} and l_{no} respectively. These regions are most conveniently written in terms of the dopant concentrations :

$$l_{po} = \sqrt[2]{\frac{2\epsilon_s\Phi N_d}{qN_a(N_a + N_d)}} \quad (9)$$

and

$$l_{no} = \sqrt[2]{\frac{2\epsilon_s\Phi N_a}{qN_d(N_a + N_d)}} \quad (10)$$

Understanding the depletion regions is crucial in thin film devices and when working with low mobility materials.

Another important relationship that the doping concentrations have is the rate at which electrons can move through the crystal structure. Denoted as J_s , this is the maximum rate of electron flow across the junction. Using Ohms law and the derived junction field in Equation (8), the J_s in a homogeneous material is:

$$J_s = qni^2\left(\frac{\sqrt[2]{D_n}}{N_a\sqrt[2]{\tau_n}} + \frac{\sqrt[2]{D_p}}{N_d\sqrt[2]{\tau_p}}\right) \quad (11)$$

where D_p, D_n, τ_p and τ_n are the diffusion coefficients and carrier lifetimes of the material for holes and electrons respectively[11].

2.7.1 The PN Junction under Illumination.

In order to understand what occurs within a semiconductor crystal during illumination, the events occurring without illumination must first be understood. Within a non-illuminated crystal structure at a temperature above absolute zero, electrons are not simply sitting around waiting for something to happen. They are constantly in motion, gaining and losing energy from various sources. When an electron gains

enough energy to transition from E_v to E_c this is considered generation. Recombination is when an electron loses energy dropping from E_c to E_v [11]. Many aspects of a crystal may affect the rate of generation or recombination such as energy traps or dangling bonds caused by impurities or physical differences between the elements of the crystal. Regardless of the source, under thermal and optical equilibrium, dark and temperature controlled environment, the two rates equal each other reaching an equilibrium.

Under solar illumination, or during a change in temperature, the generation rates are different leading to the addition of two other possibilities which are; Generation Dominant, in which the number of excited electrons is greater than the number of electrons losing energy over a given period of time and Recombination Dominant, in which the number of excited electrons is less than the number of electrons losing energy over a given period of time. This phenomena has been analyzed numerous times leading to the overall observation of the net recombination rate[10], U , where:

$$U = \frac{pn - n_i^2}{\tau_p(n + n_i \exp[\frac{E_t - E_i}{kT}]) + \tau_n(p + n_i \exp[\frac{E_i - E_t}{kT}])} \quad (12)$$

In Equation (12), τ_p & τ_n are the approximate lifetimes of an acceptor or donor, p & n are the acceptor/donor concentrations, n_i is the intrinsic donor concentration, k is Boltzmann's constant, T is temperature in kelvin, E_t & E_i are the trap energy/intrinsic Fermi levels of the material. From this relationship, the generation and recombination phenomena can be described more simplistically by the following[11]:

- $U > 0$, Recombination Dominant
- $U < 0$, Generation Dominant
- $U = 0$, Equilibrium

2.8 Fabrication of Solar Cells

Solar cells are devices that use the photoelectric effect to convert light to usable electricity. Simply put, a solar cell is a PN Junction that is exposed to a light source. Therefore, the process used to create a solar cell is similar to the one used to create a diode. Because a solar cell is formed in the same fashion as a diode, it too has the same current voltage relationship described by:

$$I = I_s * \exp\left(\frac{qV_a}{kT} - 1\right) \quad (13)$$

Typical device fabrication begins with a substrate material that is doped with an electron donor or hole acceptor. Following doping of the substrate, a thin layer of another doped material is placed onto the substrate. As shown in Figure 11, if the substrate was N-Type, then a P-Type material will be deposited over the substrate to form the junction. Once both doped materials are in contact with each other, the

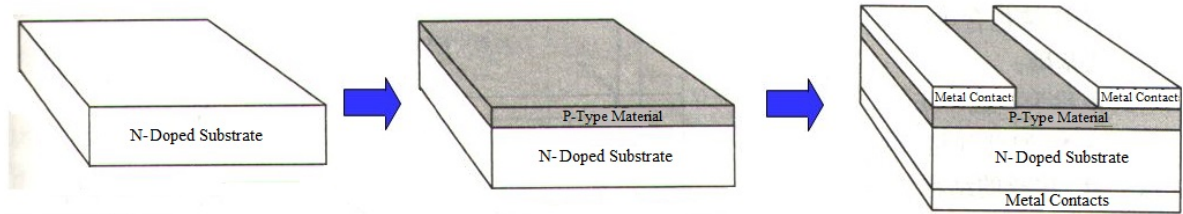


Figure 11. Generic overview of the solar cell creation process[20].

junction must be activated. Activation occurs when the substrate is baked at a given temperature, as shown in Figure 12[25]. The time and temperature in which the substrate is baked depends on the materials used and the depletion region desired. Once activated and the cell has cooled, the electrical contacts can be deposited. The contacts consist usually of grid patterns in which a metal is deposited over, leaving a similar metal grid pattern on the cell[20]. This process is completed on both sides

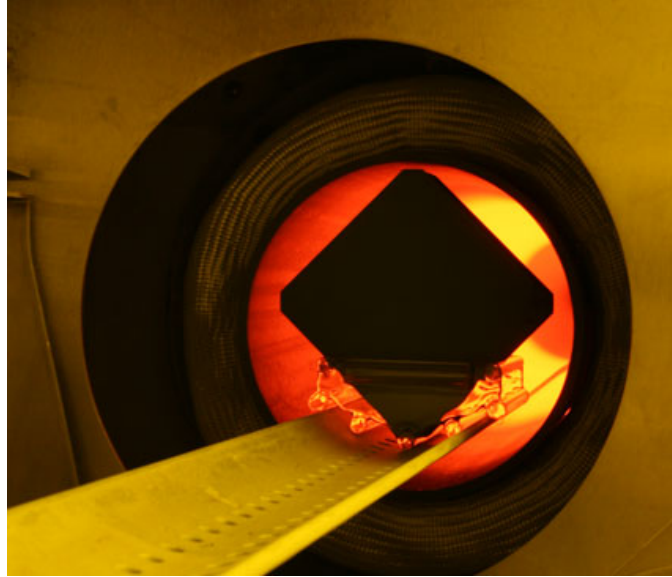


Figure 12. Commercial solar cell in annealing furnace with solar cell moving through the furnace[25].

of the cell forming both the positive and negative contacts for connection to external devices.

2.8.1 Deposition Methods.

Standard processing consists of the use of many different methods of depositing materials. These methods differ in their operating temperatures or pressures as well as the level of control over deposition and growth rates of the materials.

The first of one such process is sputtering. Sputtering is a process that directs a plasma at a source target composed of the material to deposit. This plasma knocks some of the target material free. These free atoms migrate to the substrate material surface. As they contact the substrate they bond, usually due to Van Der Waals forces, coating the surface. This results in a "hilly" layer of the deposited material. See Figure 13 for a description of this process.

Another method of deposition is Plasma Enhanced Chemical Vapor Deposition (PECVD), in which a substrate is placed in vacuum and heated. Reactants are

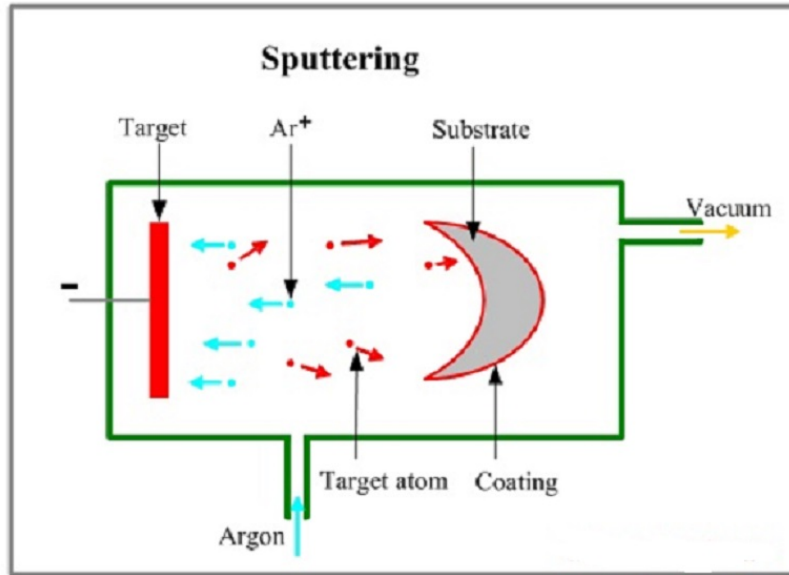


Figure 13. Sputtering process layout showing how material is deposited onto a substrate from the material target[26].

pumped into the chamber and pulled across the substrate by means of a vacuum or inert gas flow. As flow occurs over the substrate, the heated surface serves as a reaction site for the reactants. The type of bond as well as thickness of the layer depend on flow rate inert gas, power of the plasma, temperature of the substrate and processing time. PECVD allows for greater control of layering and is slightly more uniform than that of sputtering. Typically this method is used for thin film applications where the thickness of the deposited layer has somewhat strict boundaries. See Figure 14.

While both the above methods are quite effective, some applications require even greater levels of control. This brought about the process of Atomic Layer Deposition (ALD). ALD is similar to PECVD in that they are both reactant driven processes, where reactants are pulled over a heated substrate in vacuum. Instead of simply pumping all reactants simultaneously (as is done in PECVD), ALD is a cyclic process in which reactants and precursor compounds are pumped in cycles to create one atomic layer of a new alloy. This process is summarized in Figure 15. For exam-

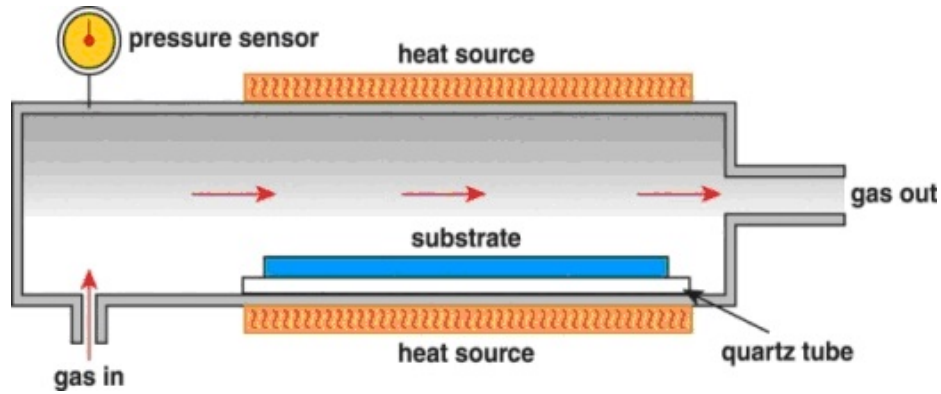


Figure 14. Chemical vapor deposition process; layout showing how materials are grown onto a substrate surface[26].

ple, Al_2O_3 is formed by first depositing trimethylaluminum which ideally deposits a monolayer of methylated aluminum. The methylated aluminum is then exposed to water as the reactant, oxidizing this layer and leaving a monolayer of Al_2O_3 on the surface of the substrate [27].

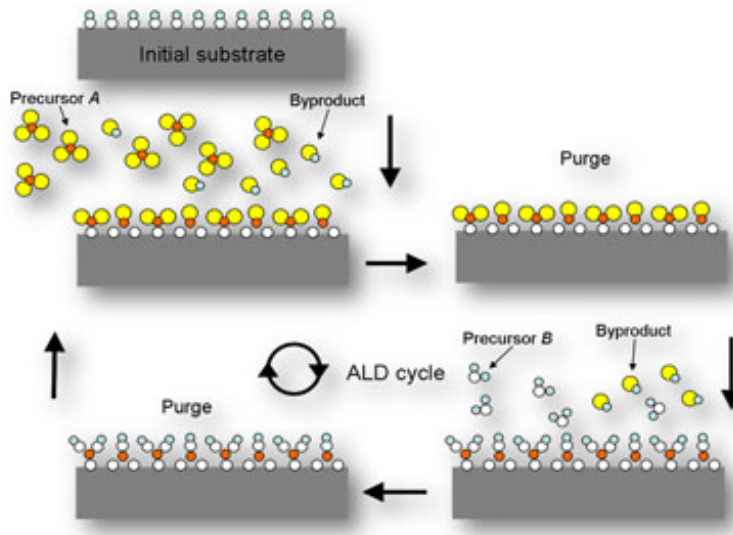


Figure 15. Atomic layer deposition process; layout showing how materials are grown onto a substrate surface[26].

2.8.2 Photolithography.

Photo-Lithography is the process in which a light sensitive material is layered over a surface and exposed to a particular pattern of light and developed in order to create the exposed pattern on the surface being covered. Following this, materials can be deposited in the same pattern that was exposed. Following depositions, the light sensitive material is removed leaving the deposited materials in the desired pattern.

2.8.3 Thermal Annealing.

There are two types of annealing processes typically used during a solar cell fabrication process, the first is the furnace anneal described in Section 2.7 for the junction activation. The second is one of the last steps during fabrication, before application of an Anti-Reflective Coating (ARC), the Rapid Thermal Anneal (RTA). Both heating processes are simply heating the sample to a given temperature for a particular duration. The activation anneal, however, is a slow rise in temperature during the heating step and a slow drop during cool down. The material is also typically held at the annealing temperature for a long duration of time. The RTA is quite the opposite and is typically used to lock everything in place by shocking the system. This process consists of rapidly heating and cooling the material allowing the already existing bonds to react rapidly forming tighter bonds. Ultimately this results in better ohmic connections at metal-semiconductor junctions and a more stable overall atomic structure. In contrast to the activation anneal, the RTA process is typically only a few seconds in duration.

2.9 Parameters for Solar Cells

Solar cell parameters range from fabrication variables to operation variables. During production, the parameters mentioned in Section 2.7 tend to have the most relevance.

2.9.1 Ideal Power.

One such parameter that directly translates from production to operation is the electric field defined in Equation (8). For an ideal junction, this electric field is approximately the V_{oc} , which is the voltage produced by the cell for use in external circuits [13]. Similar to the V_{oc} , the I_{sc} is related to a previously defined value, the J_s of the junction and is defined in Equation (11). Unlike the V_{oc} , I_{sc} is dependent upon the intensity and wavelength of light with which the cell is illuminated as well as the surface area being illuminated. With both of these parameters the ideal power that the cell is able to produce can be found using ohms law, resulting in:

$$P_{ideal} = V_{oc} \times I_{sc} \quad (14)$$

2.9.2 The IV Curve.

In order to accurately determine the performance of a solar cell, the cell must be tested under different load conditions, or resistances. In order to create an IV curve, the voltages and currents produced by the cell under illumination, for linearly increasing load values are measured and plotted against each other. This produces the solid line curve similar to the one shown in Figure 16.

The maximum area filled by a box created using the (0,0) point, as the bottom left corner, and a single point along this curve, as the top right corner, gives the maximum operating current and voltages, I_{mp} and V_{mp} . The more square the curve,

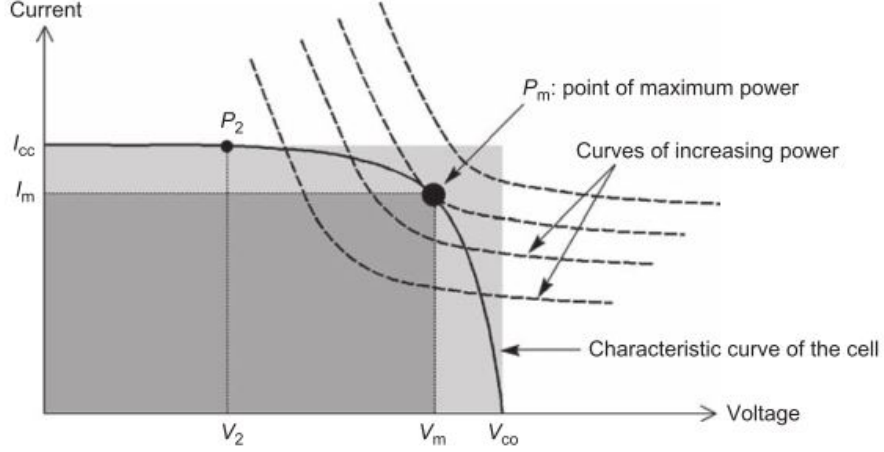


Figure 16. Voltage vs Current curve of an arbitrary solar cell with power curves showing various theoretical load conditions to demonstrate maximum power point[19].

the higher the maximum power[19]. Where the maximum power (P_{max}) a cell can produce is calculated by:

$$P_{max} = V_{mp} \times I_{mp} \quad (15)$$

From this P_{max} and P_{ideal} the fill factor (FF), described in Equation (16), is one parameter of importance for characterizing a solar cell. The fill factor is simply a ratio of the operating power to ideal power. This ratio is essentially a way of stating how close to the theoretical values a cell is operating.

$$FF = \frac{P_{max}}{P_{ideal}} \quad (16)$$

2.9.3 Efficiency.

Another important parameter to consider in cell characterization is the efficiency of the cell. This is often measured using STC which is defined as: solar radiation of $1000 \frac{W}{m^2}$, at a temperature of $25^\circ C$ and 1.5 AM. The efficiency is then described as the ratio of max power measured over the input power to the cell in illumination over

the surface area:

$$\eta = \frac{P_{max}}{E \times S} \quad (17)$$

where P_{max} is described in Equation (15), E is the illumination in $\frac{W}{m^2}$ and S is the surface area of the cell in m^2 [28].

2.10 Anti-Reflective Coating

When light interacts with a medium, such as glass, a portion of the light transmits through while another portion is reflected back. This phenomena is described in Section 2.4. In the most common material used in solar cell production, Si, this *reflection loss* effectively reduces the input radiance power by 31-48% [29]. In order to reduce or eliminate these reflections an ARC is used. The ARC works by phase shifting light around a particular wavelength by a total of π radians, or 180° . This shift causes a destructive interference with the reflected light allowing more of it to be absorbed. Applying this concept, shown in Figure 17, the lowest reported reflected percentage on a solar cell after applying an ARC is 3.79% [29]. In essence, an ARC improves the overall efficiency by reducing reflectance for the majority of wavelengths the cell can absorb and filtering some of those that the cell cannot absorb[30]. The thickness of material (d) necessary depends on n and λ for which the reflections should be suppressed. The relationship is given in Equation (18)[12].

$$d = \frac{\lambda}{4 \times n} \quad (18)$$

2.11 Multi-Layered Solar Cells

The operation described in Section 2.7 is only effective for incident light that has energy equal to or greater than E_g . Light with energy less than this will not be absorbed, reducing efficiency as that portion of the incident energy is now passing

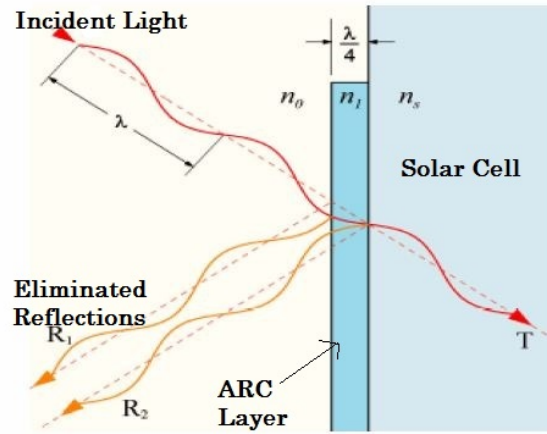


Figure 17. Visual depiction of how an anti-reflective coating works using Snell's Law and wave properties of light[20].

through the device instead of being absorbed. In order to eliminate this and absorb as much energy as possible, layers of solar cells are made to absorb select ranges of the light spectrum. By breaking up the spectrum into different regions, the overall efficiency of the device is improved although the individual cell efficiency may still be low. The multi-layered approach to improving efficiency, however, introduces new areas of consideration when designing and manufacturing solar cells.

2.11.1 Lattice Constants.

While the basic theory of two materials coming into contact and bonding is simple, the actual formation is not quite the same. Elements and compounds form crystalline structures with unique lattice constants, (α). This constant is essentially a measure of the physical distance between the atoms of the crystal structure. When two materials come into contact, this constant is one factor that determines if bonding will occur. A lattice match doesn't have to be perfect, but differences in length cause variations of strain on the crystal structure as shown in Figure 18. Some of these strains can be beneficial in that they can change the band gap of the material. These phenomena have shown to have interesting effects, primarily in Silicon-Germanium

($Si_{1-x}Ge_x$) devices. For example, by using the proper composition for x , as well as n-type dopants, a SiGe laser diode was demonstrated, operating at ~ 1590 - 1610 nm at room temperature[31]. Regions where no bond occurs are called dangling bonds and create energy traps that may trap photons but not contribute to the power generation of the cell.

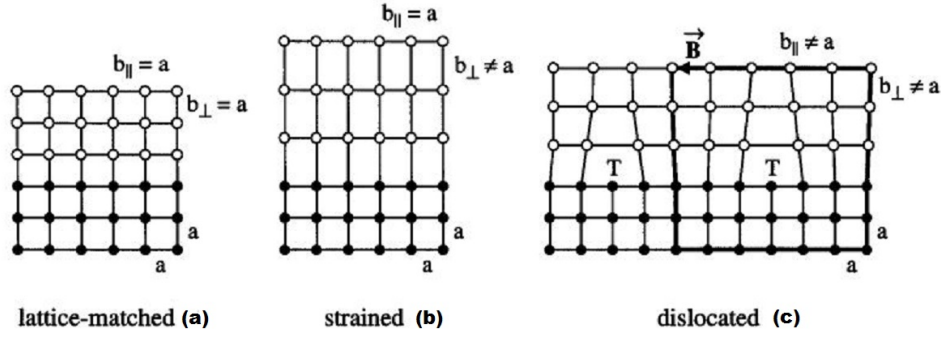


Figure 18. Visual representation of: two materials with equal valued lattice constants (a), two materials whose lattice constants are close in value but not equal (b) and two materials whose constants differ greatly(c)[11].

2.11.2 Tunneling Junctions.

Due to lattice mismatching, sometimes growing multiple junctions one on top of another is simply not possible. In order to circumvent this, a thin layer of another material with an intermediate lattice constant is used to allow the two materials to join. This layer is selected such that it allows for a physical bond to both materials. In other words, its lattice constant should be as close as possible to half the sum of the lattice constants of the two materials it is meant to connect. This tunneling layer is deposited thin enough so as to not significantly impede electrical operation, see Figure 20 and Figure 19. While this may effectively join multiple PN junctions together, the effectiveness of such a connection introduces other limitations, such as a bottleneck effect at the junction. Essentially, as an electron travels from one material to another,

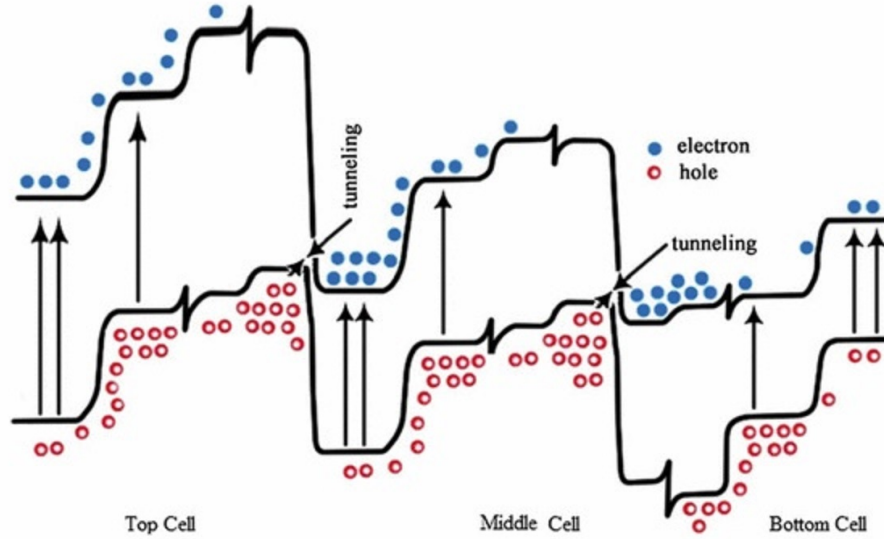


Figure 19. Band gap representation and theory of operation of a tunnel junction of a triple layered solar cell structure[11].

it must traverse at least two awkward junctions instead of simply riding along its own conduction band, shown in Figure 20[32]. This has been observed in studies regarding the electrical characteristics of tunnel junctions where it was demonstrated that as current increases to $2-7 \frac{A}{cm^2}$ the device efficiency decreases [33]. This indicates that tunnel junctions in devices would significantly lose efficiency at currents greater than a given threshold.

2.11.3 Mechanical Stacking.

With lattice constants remaining an issue for even tunnel junction structures, other methods to circumvent this problem have been investigated. Mechanically stacking essentially treats each junction as an individual circuit element and electrically connects them into one superstructure. The two main methods in ensuring the junctions are bound involve epoxy (glues) and wafer bonding (welding). This provides more freedom of materials to choose from since the lattice constant restriction is lifted. It shifts more focus to the electrical characteristics of the cell. This introduces new,

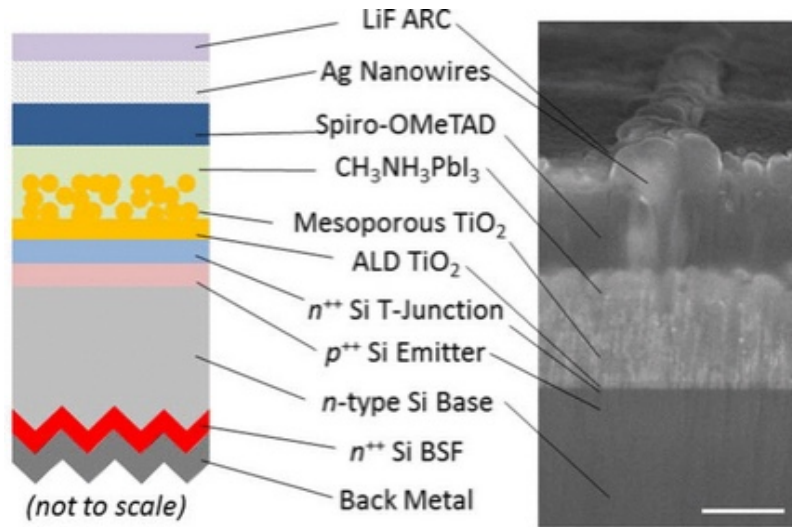


Figure 20. Two terminal junction formed using perovskite and an amorphous solar cell, demonstrating effective use of tunneling junctions[32].

but potentially more manageable problems, see Figure 21[34],[35]. This is the type of structure similar to that selected in the HMJT configuration shown in Figure 22.

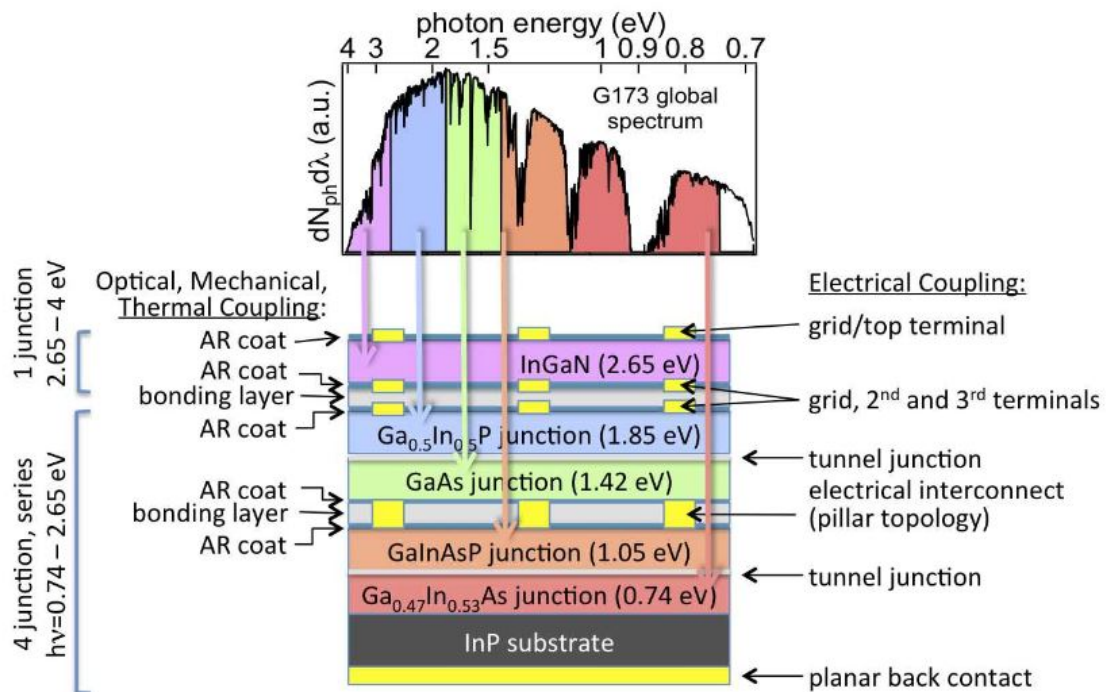


Figure 21. Quad-Junction Solar cell using tunneling and mechanical stacking to form a solar cell structure to absorb light up to $\lambda \approx 1675\text{nm}$ [35].

2.12 Hybrid Multi-Junction Tandem Devices

The primary advantages of the HMJT architecture are an increase in the optical path and improved thermal management. With this structure, the sunlight must

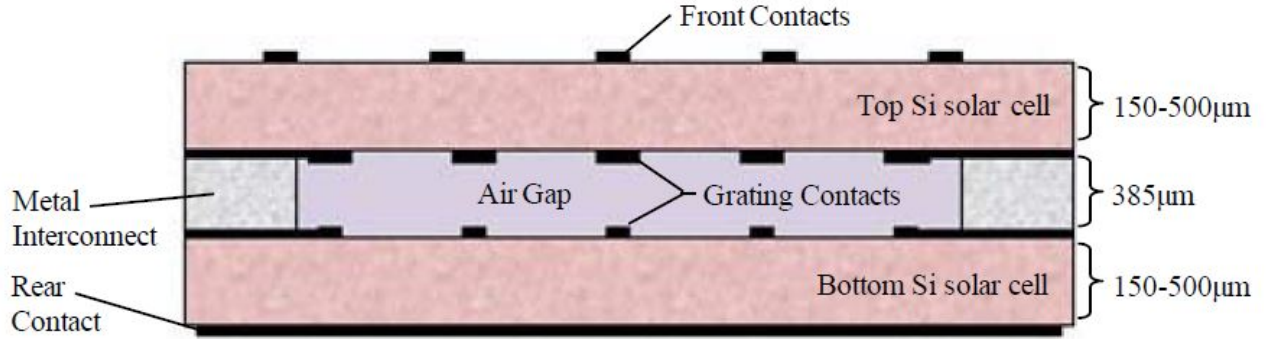


Figure 22. HMJ-Si solar cell structure demonstrating mechanical stacking and air gap cooling[36].

travel the thickness of both cells twice, assuming it doesn't simply pass through both cells, resulting in four times the optical path length. This greatly increases the likelihood of absorption. The addition of the air gap between the two cells provides a means for constructive interference which refocuses and concentrates remaining light on the secondary cell. The air gap also provides a means to remove heat, since the two cells are physically isolated with a channel for air flow between the two, there is more surface area for cooling as well. This ability to self-regulate heat also improves overall performance of the two cells[36],[37].

2.13 Chalcogenide Materials

Materials that are combinations of Sulfur (S), Se and Tellurium (Te) make up the family called ChGs. ChGs react differently depending on their temperature which give them unique advantages over other materials.

2.13.1 Photo-darkening/Photo-bleaching.

ChG materials irradiated by low power wavelengths near the material E_g energy have shown an increase in optical absorption. Some studies, however, suggest this is not required as similar results could be reproduced using below-band-gap light.[38] This effect of photo-darkening is essentially a temporary lowering of the band-gap. Similar to this, photo-bleaching is generated in the same manner, but has the effect of widening the band-gap, shifting it towards lower wavelengths.

2.13.2 Other Photo-induced effects.

Many other phenomena such as photo-compaction and photo-contraction which are optically induced structure changes in which the atoms are condensed or dispersed, respectively, the latter reversible by thermal annealing. Incident radiance at or below the band gap of the ChG causes a restructuring of the atoms, believed to be related to micro temperature changes. These characteristics have been demonstrated to have photo-mechanical applications in experiments conducted using Al_2O_3 on a cantilever radiated with near band gap light caused mechanical deflections[38].

2.14 Energy Dispersive X-Ray Spectroscopy

There are many different methods available to analyze a material in order to determine what elements exist within it. One such method is that of energy dispersive x-ray spectroscopy (EDS). In this method of spectroscopy, samples are scanned with high energy electrons. As these electrons interact with the material being scanned, energy is absorbed and electron hole pairs are generated[39]. These generated electrons are swept away by an applied field in which they are counted and categorized by energy level. The result is a number of counted electrons at a particular energy

level. Each element has its own signature of energies and can be identified using scans with appropriate energy over a long enough period of time.

Figure 23 shows a basic overview of how EDS looks inside a crystal structure. Here the X-ray escape depth (d) into a material depends on primarily the material density and the energies used, leading to the equation:

$$d = 0.033 * \frac{p * Z * (E_o^{1.7} - E_c^{1.7})}{A} \quad (19)$$

where p is the material density, Z is the atomic weight, A is the atomic number, Ec is the desired energy to detect and Eo is the energy used in the scan[39].

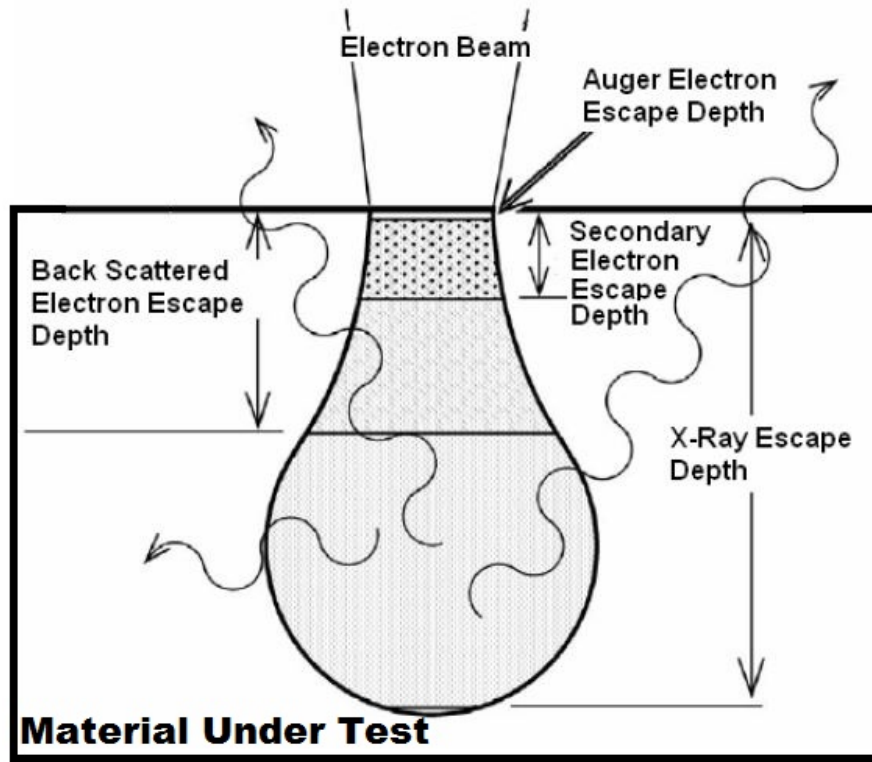


Figure 23. Depiction of EDS penetration depth into a generic material[39].

III. Methodology

This chapter describes the technologies, theoretical foundations, research methods and testing methods used throughout the course of this endeavor. It is intended to provide a solid foundation for the basis and overall intent of this research.

3.1 Near Infrared Solar Cells

The solar spectrum, as described in Section 2.6 shows that the infrared spectrum of light is the range of wavelengths at approximately 780-2200nm. However, the cutoff wavelength at which the majority of commercially available solar cells, which are Si based, no longer absorb light for use in the photoelectric effect, using Equation (3), is around 1100nm. In order to extend the range of wavelength that can be absorbed, a lower band gap material, Ge is used for solar cell device creation. Since many devices using Ge, primarily photo-detectors, operate in the infrared region it is proposed that this will serve well as a NIR solar cell substrate. Using the same calculations for Ge that were completed on Si, noting the Ge band gap of approximately 0.67eV[23], the Ge based solar cells are expected to be effective up to approximately 1850nm. In order to create a solar cell using this substrate, P-type and N-type materials are selected and added accordingly as mentioned in Chapter II.

3.1.1 Chalcogenide Solar Cell Fabrication.

The NIR solar cell begins with selection of a Ge substrate as described in Section 2.8 and 3.1, doped with Sb making it an N-Type semiconductor. In order to expedite processing and ensure relative uniformity of substrates, the substrates were procured from the University of Michigan [40] with the following characteristics; 50.8mm diameter, <100> orientation, 500 μ m thickness and 0.01-0.1 Ω -cm resistivity. As mentioned

in Section 3.1 the upper wavelength that this material can absorb is approximately 1850nm which is within the NIR region of solar radiation. Due to recent advances using the ChG material CdTe to produce solar cells [7], GeTe was selected as the p-type material for all samples in this research. The choice to use GeTe was made due to the fact that it is naturally p-type and did not require any further processing [23]. Another factor in selecting GeTe was that it is a ChG and has unique properties, mentioned in Section 2.13, that could potentially be exploited in solar cell devices. Finally, the third factor in selecting GeTe is the low lattice constant mismatch between Ge and GeTe at approximately 0.25-0.3 Å, making them likely to bond well with minimal strain to either material at the junction. Initial proof of concept tests have been performed to ensure feasibility and consisted of a simple PN junction formed using only N-type Ge and GeTe[41]. Investigations into the addition of other materials, such as Al₂O₃ and V₂O₅, are considered as a means to improve device performance.

3.2 Band-Gap Engineering

Using the concepts described in Section 2.2 and Section 2.7 the materials selected are known to have energy band and Fermi-levels appropriately positioned to create a solar cell using fabrication techniques similar to the methods described in Chapter II. Many variables, listed in Table 1, regarding the final structure of the device band gap are investigated to develop a good understanding of the formation of the device. The approximate energy band representations used for analysis of Ge,GeTe,Al₂O₃,and V₂O₅ are shown in Figure 24[42],[43],[23],[44].

Of the materials used, the only material that does not have an intrinsic carrier concentration that is used during device processing is Ge. Because of this, all other materials are initially assumed to have an intrinsic concentration of carriers when considered in calculations. The Fermi-level for Ge, although given a range from manufacturing,

had to be determined using data collected from four-point probe measurements and Equation (2), 7 and 6. Comparisons to manufacturer, other published data and these measurements are in agreement.

Table 1. Sample trial processing layout with identified variable under test for each sample set.

Sample	Testing	Variable
1A	Junction Formation	Anneal Environment (Atmosphere)
1B	Junction Formation	Anneal Environment (Vacuum)
2A	Junction Formation	None
3A	Voc	Interfacial Layer (Material Thickness)
3B	Voc	Interfacial Layer (Material Thickness)
4A	Voc	Activation Method(RTA vs Anneal)
4B	Voc	Activation Method(RTA vs Anneal)
5A	Voc	Interfacial Layer (Material Thickness)
5B	Voc	Interfacial Layer (Material Thickness)
5C	Voc	Interfacial Layer (Material Thickness)
6A	Voc	Interfacial Layer (Material / Outer Layer Thickness)
6B	Voc	Interfacial Layer (Material / Outer Layer Thickness)
6C	Voc	Interfacial Layer (Material / Outer Layer Thickness)
7A	Voc	Interfacial Layer (Material Thickness)
7B	Voc	Interfacial Layer (Material Thickness)
7C	Voc	Interfacial Layer (Material Thickness)
8A	Voc	Interfacial Layer (Material / Outer Layer Thickness)
8B	Voc	Interfacial Layer (Material / Outer Layer Thickness)
8C	Voc	Interfacial Layer (Material / Outer Layer Thickness)
9A	Voc / Isc	Anneal Time / Temperature
9B	Voc / Isc	Anneal Time / Temperature
9C	Voc / Isc	Anneal Time / Temperature
10A	Voc / Isc	Capping Layer / Anneal Time / Temperature
10B	Voc / Isc	Capping Layer / Anneal Time / Temperature
11A	Voc / Isc	Capping Layer / Anneal Time / Temperature
11B	Voc / Isc	Capping Layer / Anneal Time / Temperature

The use of two different Ge based materials limit issues such as lattice mismatch described in Section 2.11.1. Given the close proximity of band gaps between GeTe and Ge, 0.87 and 0.67 respectively [23], allow for high absorptivity of light below 1850nm.

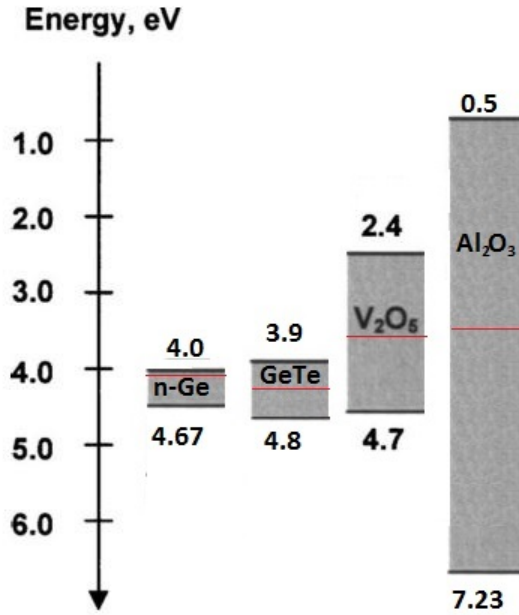


Figure 24. Energy band representations of Ge, GeTe, Al₂O₃ and V₂O₅[23],[44],[45],[46][47].

3.3 Modeling and Simulation

MATLAB software is used in performing all calculations of parameters from the outcomes of testing procedures. Since most test equipment available use different means of exporting data MATLAB is also the means used to combine and normalize test data for display in tables and graphs. For simulation and calculations, the fundamental equations for homogeneous PN junction formation are the basis used for calculations performed. These equations are found to have comparable results to their non-homogeneous counterparts and are used for these cases as well[28].

The primary choice in use of simulation software is to aide in repetitive calculations on large sets of data. These are used to determine the end parameters, such as barrier voltage, current density, etc., based on initial analysis of R_s and processing data from each stage of testing samples. Each surface (Ge and GeTe) is tested with a four-point probe to measure R_s both before and after junction activation steps. These values are

then converted to ohm-cm resistivity values for the sample and used to determine the approximate dopant (N_a or N_d) concentrations. Using these values, the predicted current densities, junction voltages, approximate remaining carrier concentrations and the generation and recombination rates are computed for each sample. The initial predictions for a NIR solar cell are performed using Equation (6), Equation (7) and Equation (8). To determine initial predicted values, the published data for GeTe sheet resistance and carrier concentrations as well as the manufactured values for Ge are used. Using Equation (6) the value for ρ is determined and used in Equation (7) to obtain the approximate dopant concentrations N_a and N_d . Once these are determined the predicted voltages from each configuration are determined. Since each device is an electric element, the total device voltage is the sum of each of the layered junctions.

3.4 Cell Fabrication

Device fabrication follows processes similar to that of the industry standard for solar cell creation, described in Chapter II. A few of the process followers used are listed in Appendix B. The overall process is described in further detail in the following subsections.

3.4.1 Cleaning.

The first step in all processing procedures is to clean the sample. Cleaning the sample is important to ensure that no foreign materials are on the surface. Foreign materials such as oils from improper handling or small particles present from the environment may cause unfavorable interactions with the layers of materials. They could even prevent the desired interaction pursued during the fabrication process. Because of this, great care and multiple cleaning steps take place throughout the

fabrication process, typically done before a deposition step. The cleaning process shown in Table 2 is the method used whenever cleaning is necessary.

Table 2. Procedures used to clean all samples prior to depositions of materials.

Step	Duration
Spin on Spinner 500rpm	-
Flood With Acetone	30 Sec
Flood With Methanol	30 Sec
Flood With De-Ionized Water	30 Sec
Flood With Isopropanol	30 Sec
Dry with Nitrogen	30 Sec

3.4.2 Deposition Layers.

The primary means of junction forming and manipulation is achieved through a process of layering of materials. Therefore, the type of materials layered, along with their orientation in relation to one another, are the primary means planned to engineer a suitable single PN junction solar cell device. The test layers used are outlined in Table 3. Primary deposition sources for active semiconductor materials are sputtering, PECVD and ALD, described in Section 2.8.

Prior to depositing layers, after cleaning, samples had any native oxide layers removed. This step is mentioned separately from cleaning as not all layers react the same with the environment to form an oxide layer. Also, some layers used are themselves an oxide layer and removing these during cleaning would serve no purpose. Therefore this step is only utilized as necessary. The process of removing oxide layers is achieved through a short rinse in a diluted Hydrofluoric Acid (HF) solution called a buffered oxide etchant (BOE), followed by a rinse with deionized water and dried with nitrogen. This ensures the exposed surface is moderately free of any oxides and is the intended surface in which deposition is to occur.

Table 3. Physical structure of samples tested during this research. Patterned contacts placed on front side of sample, solid sheet of metal on back side. Metal contacts consist of titanium adhesion, aluminum body and gold cap to prevent oxidation.

***- indicates layer needed for processing but removed before final testing.**

Sample	Substrate	Finish	Layer 1	Thickness(nm)	Layer 2	Thickness(nm)	Layer 3	Thickness(nm)
1A	n-Ge	Polished	GeTe	200	N/A	N/A	N/A	N/A
1B	n-Ge	Polished	GeTe	200	N/A	N/A	N/A	N/A
2A	n-Ge	Polished	GeTe	200	N/A	N/A	N/A	N/A
3A	n-Ge	Polished	Al ₂ O ₃	3	GeTe	200	N/A	N/A
3B	n-Ge	Polished	Al ₂ O ₃	5	GeTe	200	N/A	N/A
4A	n-Ge	Unpolished	Al ₂ O ₃	3	GeTe	200	N/A	N/A
4B	n-Ge	Unpolished	Al ₂ O ₃	3	GeTe	200	N/A	N/A
5A	n-Ge	Polished	Al ₂ O ₃	0.5	GeTe	200	N/A	N/A
5B	n-Ge	Polished	Al ₂ O ₃	1	GeTe	200	N/A	N/A
5C	n-Ge	Polished	Al ₂ O ₃	2	GeTe	200	N/A	N/A
6A	n-Ge	Unpolished	GeTe	200	Al ₂ O ₃	10	N/A	N/A
6B	n-Ge	Unpolished	GeTe	200	Al ₂ O ₃	25	N/A	N/A
6C	n-Ge	Unpolished	GeTe	200	Al ₂ O ₃	50	N/A	N/A
7A	n-Ge	Polished	GeTe	10	Al ₂ O ₃	50	N/A	N/A
7B	n-Ge	Polished	GeTe	50	Al ₂ O ₃	50	N/A	N/A
7C	n-Ge	Polished	GeTe	30	Al ₂ O ₃	50	N/A	N/A
8A	n-Ge	Polished	GeTe	10	V ₂ O ₅	50	Al ₂ O ₃	50
8B	n-Ge	Polished	GeTe	10	V ₂ O ₅	50	Al ₂ O ₃	50
8C	n-Ge	Polished	GeTe	10	V ₂ O ₅	50	Al ₂ O ₃	50
9A	n-Ge	Unpolished	GeTe	175	Al ₂ O ₃	50	N/A	N/A
9B	n-Ge	Unpolished	GeTe	175	Al ₂ O ₃	50	N/A	N/A
9C	n-Ge	Unpolished	GeTe	175	Al ₂ O ₃	50	N/A	N/A
10A	n-Ge	Polished	GeTe	10	N/A	N/A	N/A	N/A
10B	n-Ge	Polished	GeTe	10	N/A	N/A	N/A	N/A
11A	n-Ge	Polished	GeTe	10	*Si ₃ N ₄	100	N/A	N/A
11B	n-Ge	Polished	GeTe	10	*Si ₃ N ₄	100	N/A	N/A

3.4.3 Photolithography.

Prior to use of photolithography processes as described in Section 2.8.2, samples are cleaned. They then have a layer Microposit S1818 series photo resist deposited following the process shown in Figure 25. A layer of approximately $2\mu\text{m}$ is deposited in order to accommodate the metallization processes. This ensures that a large enough gap exists between materials that are staying and going. This gap is necessary due to the possibility of the contact metals and masked metals sagging and inadvertently connecting. If they connected, it would potentially allow the contact metals to be removed during lift off. After photoresist is deposited, a soft bake is required at approximately 110°C for 1-2 minutes in order to prepare the photo resist for Ultraviolet

(UV) exposure. This allows the exposed areas to cross link such that they will react with the developer solution and be removed from the substrate surface. After the soft bake, samples are covered with a chrome mask and exposed to UV light. The exposed regions, which are now cross-linked, are developed, or removed, using a Microposit Developer 351 solution that is three parts deionized water, one part developer. Following the developing process, samples are inspected and any incomplete processing steps are repeated if necessary. The overall process ends with a final deionized (DI) rinse and dry with nitrogen gas to remove any loose materials or remaining moisture.

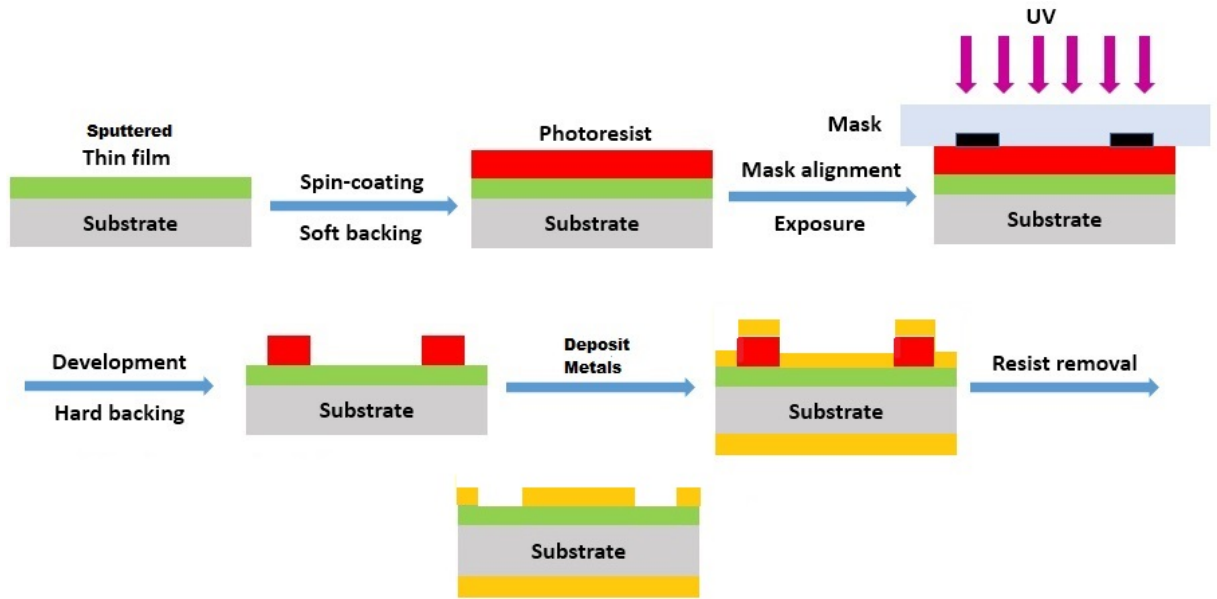


Figure 25. Photolithography process used for contact patterning.

3.4.4 Metallization.

In order to create a connection from the semiconductor solar cell to test equipment, metal contacts are necessary. To create these, Aluminum (Al) is used as the primary contact for all surfaces other than GeTe because of its low cost and electron affinity. Because Al readily forms an oxide layer when exposed to oxygen[48], Al contacts have a thin layer (approximately 200 Å) of Gold (Au) deposited at vacuum in order

to encapsulate the surface, preventing, or at least reducing, oxidation.

Au is the primary metal used for GeTe due to its electron affinity. These selections are necessary in order to form a low resistance or ohmic contact to the GeTe[37]. Given the materials available in the clean room at Air Force Institute of Technology (AFIT), Au and Al are the only viable candidates. All metal-semiconductor junctions have trace amounts of Titanium (Ti), (approximately 200 Å) deposited first to aid in physical adhesion of the materials during the processing steps. Since Ti has strong physical adherence to most surfaces, and in order to reduce the chance of inadvertently removing the wrong materials during processing, it was decided that this layer is beneficial with little to no adverse affects.

3.4.5 Annealing.

Activation annealing for most samples is performed at 400°C for 30 minutes in atmosphere. This temperature and time are sufficient to create a junction but limit sublimation of Te[49]. Due to limitations on available equipment able to anneal at the required temperature, a lower temperature anneal, 250°C, with a much longer duration of up to 3 hours is also tested to determine if the 400°C temperature is necessary. The proposed annealing profile for each sample is shown in Table 4. In order to set contacts and finalize the device, an RTA is performed at 640°C. The duration of RTA is 20 second as it has been shown to be effective in rudimentary device creation[37]. The RTA profiles for all samples, prior to ARC deposition, are shown in Table 4.

Table 4. Annealing profile used for all samples tested.

Sample	Aneal Temp	Aneal Time	RTA Temp	RTA Time
1A	400°C	30 min	640°C	20 sec
1B	400°C	30 min	640°C	20 sec
2A	400°C	30 min	640°C	20 sec
3A	400°C	30 min	640°C	20 sec
3B	400°C	30 min	640°C	20 sec
4A	400°C	30 min	640°C	20 sec
4B	400°C	30 min	640°C	20 sec
5A	400°C	30 min	640°C	20 sec
5B	400°C	30 min	640°C	20 sec
5C	400°C	30 min	640°C	20 sec
6A	400°C	30 min	640°C	20 sec
6B	400°C	30 min	640°C	20 sec
6C	400°C	30 min	640°C	20 sec
7A	400°C	30 min	640°C	20 sec
7B	400°C	30 min	640°C	20 sec
7C	400°C	30 min	640°C	20 sec
8A	250°C	120 min	640°C	5 sec
8B	250°C	120 min	640°C	5 sec
8C	250°C	120 min	640°C	5 sec
9A	250°C	60 min	640°C	5 sec
9B	250°C	120 min	640°C	5 sec
9C	250°C	180 min	640°C	5 sec
10A	250°C	60 min	640°C	5 sec
10B	250°C	120 min	640°C	5 sec
11A	250°C	60 min	640°C	5 sec
11B	250°C	120 min	640°C	5 sec

3.4.6 Anti-Reflective Coatings.

Application of an ARC is performed after contact RTA on final samples to improve their response as discussed in Section 2.10. Due to the rather high index of refraction of GeTe, $n = 5.5$ at $\lambda = 1500\text{nm}$, a Silicon Nitride (Si_3N_4) ARC coating of approximate thickness of 188nm is necessary for optimum absorption around 1500nm. This is based on results from Equation (18) and the index of refraction of Si_3N_4 of $n = 1.99$ [50].

3.5 Device Testing

Device testing covers multiple methods in order to characterize each cell appropriately. Solar response tests are completed using a solar simulator test station calibrated for STC conditions. The corresponding V_{oc} , I_{sc} and load test values obtained under

these conditions are used to generate IV curves and calculate device efficiency as discussed in Section 2.9. Samples also undergo diode characterization testing using a parameter analyzer to observe the device response to varied voltages in order to see junction performance and track junction formation. Each samples' results are plotted and labeled according to the stage in processing according to its annealing step. Diode plots labeled with a "-0AN" represent all processing steps done before junction activation. Plots with "-1AN" encompass processing done after junction activation but before a subsequent annealing.

IV. Results

This chapter consists of data obtained while performing fabrication steps and testing processes described in Chapter III. Each sample tested is labeled with an alpha numeric title to designate trial number, the iteration at which testing is performed and the variable under test. The overall summary of test parameters investigated is shown in Table 1. All data results collected are listed in the appendices under their respective area of analysis as mentioned below.

4.1 Sample configurations

Chapter III, Table 3 describes the many different layer orientations and configurations tested in order to assess their effect on the end product. The initial predictions calculated, using code shown in Appendix A, for V_{oc} and I_{sc} consisting only of the doped Ge and GeTe to form a junction, are: $V_{oc} = 210$ mV, $I_{sc} = 131\mu\text{A}$. All configurations are compared to this ideal case and discussed further in Chapter V. All samples showed an approximate range of 20-50% reflectance for the entire spectrum in which they were tested. Samples with the GeTe layer on bottom had a lower reflectance than those samples tested with GeTe on top. The Al_2O_3 layers appeared to help smooth the reflectance to an almost flat line, regardless of their position in the device, providing a more uniform response. Transmittance data showed more detail into the photovoltaic response of samples with a more narrow range of 0-20% transmittance for samples. Here the Al_2O_3 layers did appear to have a slight effect on smoothing the overall response, however the layering did not appear to have as much of an impact on the overall device formation or performance.

4.2 Sample Testing

This section is a summary of results from the various tests performed during this research. Each section has a condensed version of test results to provide a general overview of the data. All data collected for individual samples is listed in Appendix H.

4.2.1 Characterization Tests.

Samples were tested after completion of each annealing step using the Alessi probe station (model REL-6100) and Parameter analyzer (model HP 4155A). Data collected from these tests is plotted in Appendix F to reproduce the graph displayed on the test equipment. Samples were also analyzed using MATLAB script, listed in Appendix A, to determine the parameters of interest as discussed in Chapter III. Sample testing consisted of a standard diode test in which V_a is varied $\pm 10V$, in 20mV increments, and the output current is measured on a $\pm 100mA$ range. Voltage is limited to 10V to allow for decent fidelity of data while current is limited to 100mA because of equipment limitations. For uniformity of testing, the bottom side of the cell is assumed to be the cathode, connected to the negative terminal while top side of cell is assumed to be the anode and connected to the positive terminal. The results for each individual sample trial are shown in Appendix F in which the measured current is plotted vs applied voltage. All of the samples final versions are plotted together in Figure 26 for comparison. Most samples began showing a junction formation after the first anneal, the junction activation step, however some did not show junction formation until after the final RTA. Only one sample set, sample set 9, which was annealed for a longer duration at lower temperature, showed an inversion of the junction polarity compared to the other sample sets.

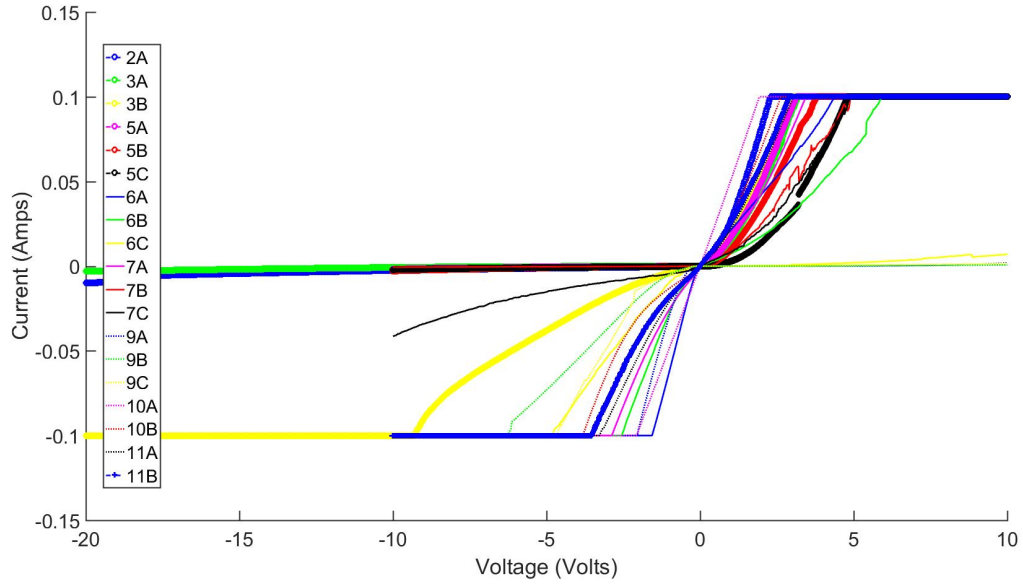


Figure 26. Current vs Voltage plot of all final diode tests for all samples.

4.2.2 Solar Simulator Tests.

After final processing and parameter analyzer tests, completed samples are tested on a solar simulator calibrated for operation at STC. Only the surface area of the sample is considered for the input power in efficiency calculations. Because of this consideration the $1 \frac{kW}{m^2}$ input power is converted to the equivalent value of $100 \frac{mW}{cm^2}$ as this is the total radiance incident on a $1cm^2$ sample [20]. Reflectance effects are also considered as failure to do so falsely represents the actual efficiency of the device. Samples are tested first without any illumination to determine dark condition values, shown in Table H-1. These values are intended to be used to verify the initially predicted leakage currents. In all samples this dark current ranged between 4-125 nA, which is on par with the values predicted. Samples are then tested with both sides of the sample illuminated, shown in Tables H-2 and H-3 for each orientation configuration. The reason for testing both sides of the sample is two-fold and this decision was made after testing of sample set 4. The first reason in testing both is

that these early sample sets had poor connections for the patterned contacts due to a lack of adhesion of metals. The results for these samples with poorly formed contacts then are only valid for the localized region in which the probe is connected. Though there sample has sections of good contacts it is not an appropriate measurement of the entire junction. The second reason for testing both sides of the samples came after visual inspections. During inspection, the GeTe surfaces appeared to be much more reflective than their Ge counterparts, indicating that more incident light may be getting reflected away than anticipated. Given the irregular pattern of adhesion and the fact that the crystallized GeTe appeared to be quite reflective, the non-patterned backside of the samples are also illuminated and results recorded as a means to try to rule out the effects of reflectance and lack of appropriate contacts. This method is effective because the cathode contact for the solar simulator test system is simply a block of Al and is therefore able to effectively contact all bottom surface metals on the sample simultaneously, fixing the problem of broken contacts.

In order to properly characterize each final sample, the cells are then tested under varying load conditions ranging from 100Ω to $10k\Omega$. These load test results are used later in Chapter V to build an IV-Curve for each of the samples as described in Chapter II. From the IV-data, each sample has its fill factor and efficiency values determined and displayed with the IV-curve shown in Appendix G. The largest fill factor obtained was 26% and the largest efficiency only 0.003%. However, Tables H-2 and H-3 in Appendix H provide a peak possible efficiency for each device that consists of just the light entering the sample, assuming the device were operating at the V_{oc} and I_{sc} values.

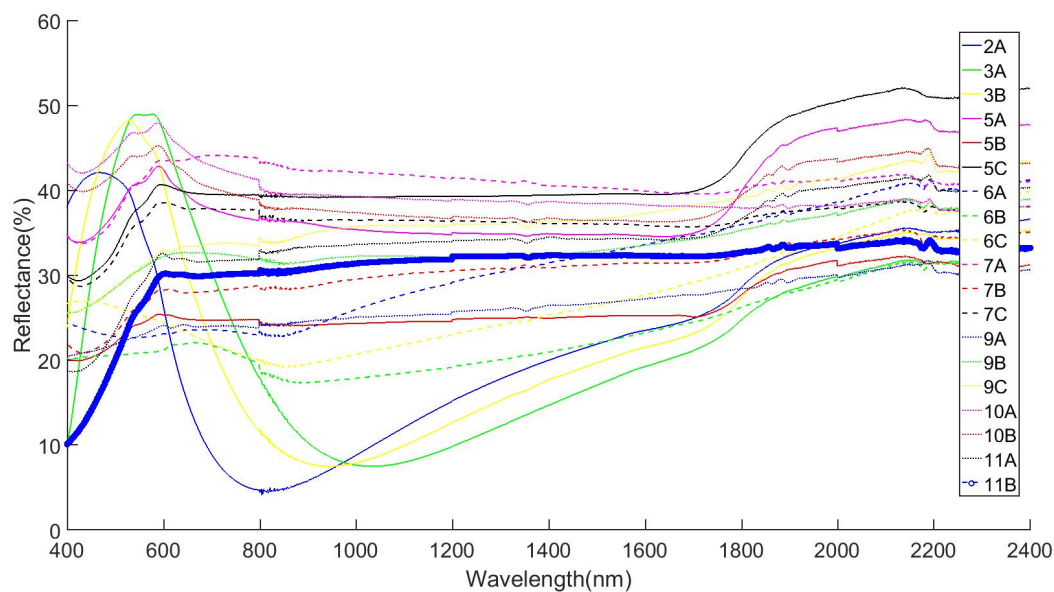


Figure 27. Reflectance percentage of all samples from 400-2400nm.

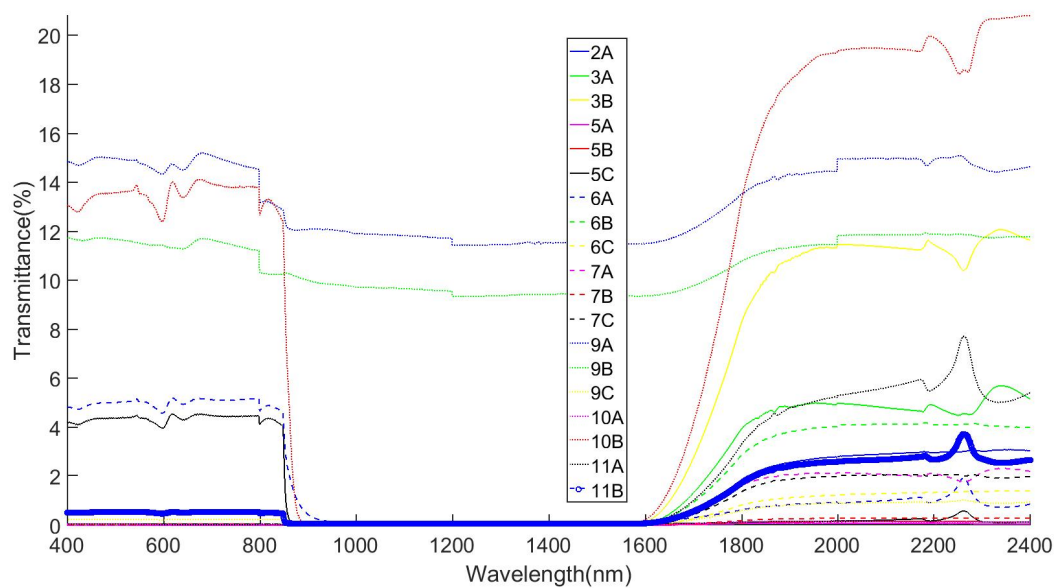


Figure 28. Transmittance percentage of all samples from 400-2400nm.

4.2.3 Reflectance and Transmittance Tests.

In order to determine an overview of cell performance in terms not related to power, reflectance and absorptivity data were collected using a Cary 5000 Spectrome-

ter. The absorbtivity data collected during testing is in effect the measured absorption coefficient of the sample for a particular wavelength. Using the relationship between transmittance, reflectance and absorbency, this data is converted to transmittance values for display and analysis. Plots of all sample sets are summarized in Figures 27 and 28. Plots for each individual sample tests are shown in Appendix E. Sample set 4 was excluded during testing since structurally it is a repeat of set 3 only with larger surface area. This size difference will not have an impact on reflectivity and transmittance and would result in duplicate data. All samples were tested in order to see the impact the layer orientation, junction formation and activation steps had on the transmittance and reflectance properties of the sample. As mentioned above, regardless of layer orientation, all samples exhibited an approximate range of 20-50% reflectivity for the entire spectrum in which they were measured, with some samples responding better at a variety of wavelengths. They all have low transmittance between 850nm and 1600nm indicating good absorption on this range of wavelengths. Some samples had better absorption in a wider range of wavelengths(400-1850nm) indicating a better junction formation. Overall, however, the worse case transmittance is 20% with a worst case reflectance of 50%, showing that the absolute worse sample is still absorbing 30% of the incident power. These variations are discussed in further detail in Chapter V.

4.2.4 Scanning Electron Microscope Tests.

The Scanning Electron Microscope (SEM) is used for imaging and Energy Dispersive X-ray Spectroscopy (EDAX) for composition data collection of samples 10A and 11A. This is done in order to collect atomic percentages of the materials within the samples in order to verify the approximate composition of GeTe and ensure an approximate ratio of 1:1 was maintained. Although GeTe naturally has a high hole conductivity as the concentration of Ge increases in GeTe, the number of acceptors decreases[23], making the material less P-type. See Figures 29 and 30 for the scan images of samples 10 and 11 respectively. Full EDAX results for each point scanned, for each sample, are listed in Appendix C. Of the entire area scanned, the Te initially consisted of around 2.5% of the scan area. After thermal processing steps, sample 11A maintained an average percentage of 2.4% Te while sample 10A showed a reduction to only 1.22%. In both samples, the Ge concentration is skewed due to the large Ge substrate and only the Te concentration is considered.

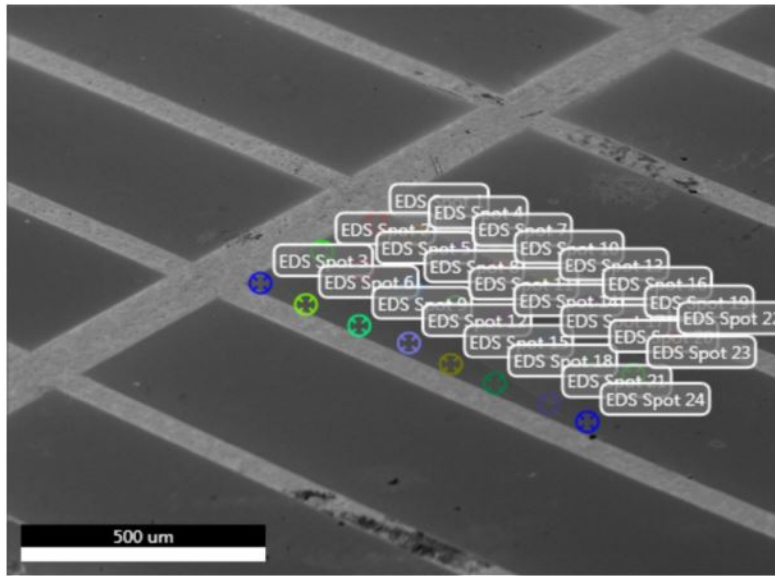


Figure 29. SEM and EDAX images and test points for sample 10A.

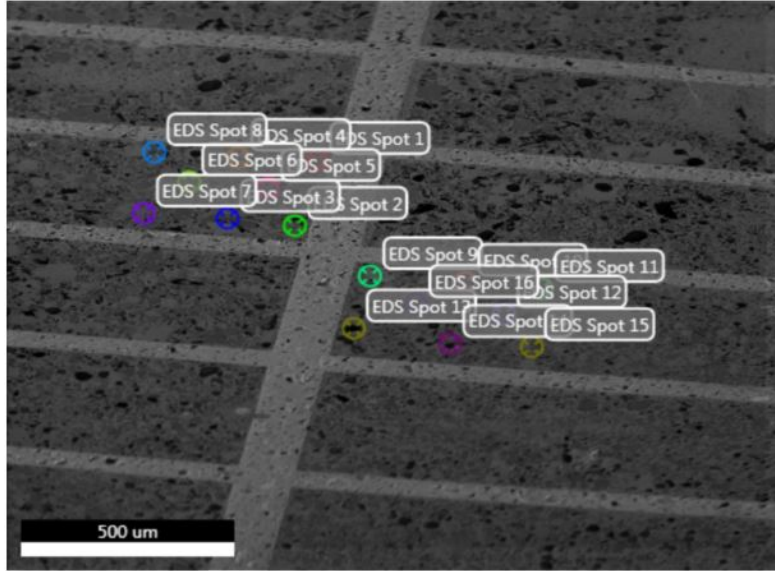


Figure 30. SEM and EDAX images and test points for sample 11A.

During scanning the cooling for the SEM/EDAX began failing, limiting the number of scans possible. Because of this, the data obtained is limited and only these two samples were tested. Even though limited data was obtained, there is an indication of a loss of approximately 50% of the Te concentration from the original GeTe.

V. Analysis

5.1 Overview

In this chapter, the findings in Chapter IV are discussed and any significant conclusions identified. The focus of discussion remains the formation and function of a Ge/GeTe PN-junction.

5.2 Junction Formation

Throughout the processing steps, samples had tests performed using a standard diode test in order to track the progression of the junction formation. The resulting current/voltage plots shown in Figure 26 and in Appendix F, indicate that almost all samples began forming a junction during the activation step as expected. The samples that did not appear to form a junction during the activation step still formed one during the final RTA step. The fact that all samples had junctions formed during the RTA even if they were not formed during activation indicates that the RTA is likely performing the activation as well and that the separate activation step could potentially be eliminated. As discussed in Chapter II the junction voltage created across the depleted region of a PN-Junction, can be approximated by Equation (13). Using the data obtained from these diode tests and another MATLAB script, shown in Appendix A, the junction voltages are calculated for each data point obtained from the diode tests. The averaged results of these calculations are summarized on Table H-5 and H-8 with the plotted results of these calculations shown in Appendix D on Figure D-1 through D-8.

While testing samples under illumination the measured voltage would rise slowly to a peak value. Once at this peak, the voltage then began to slowly decrease back down to a relatively stable value which is the value presented in Table H-2 and H-

3. Although the peak and stable values only varied by approximately of $20\mu V$ with each sample, the sporadic nature of the measured voltages and currents point to the ChG aspect of GeTe as the likely cause. Although unconfirmed, it is likely this is due to micro phase changes under illumination causing slightly differing performances depending upon the solar radiance. Photo-bleaching, photo-darkening (as mentioned in Chapter II) or other phase change phenomena may be issues decreasing the built in voltage from the predicted values, but they were not considered with this research.

5.2.1 Open Circuit Voltage Variances.

In order to address whether or not a change was effective or not, test and calculated values were compared between individual sample sets. For all comparisons, a positive value indicates a decrease in voltage where a negative value indicates an increase in voltage. As shown in Table 3 differences between set 2, set 3A/B and set 5A/B/C consist of the insertion of an inter-facial layer of 3nm, 5nm, 0.5nm, 1nm and 2nm respectively for sets 3 and 5. When compared to set 2, this resulted in an average barrier voltage change of: 11mV, 68mV, -45mV, -44mV, and -24mV respectively. From these results, the barrier height has a direct relationship to the thickness of material. In this case, the barrier height decreased the most on sample 3A which happened to be the best performing sample of set 3. Counter to this, however, sample 5A was the best performer of set 5, yet it had an increase in barrier height. This also resulted in a change in measured V_{oc} on the solar simulator of -39.5mV, -23mV, 14.6mV, 31.6mV and 34.5mV for set 3 and 5, respectively. This indicates that introduction of a thin inter-facial layer initially has a negative impact until a particular threshold is achieved. After the threshold thickness, the layer has a limited increase to the V_{oc} before it begins to have negative impact again. The peak value appears to be at a thickness of Al_2O_3 somewhere between 2-4nm.

In sample set 6, the layers of GeTe and Al_2O_3 that were used in sets 3 and 5, were switched such that GeTe is now the interfacial layer. GeTe layers all remain consistent at 200nm with the external Al_2O_3 layers deposited in thicknesses of 10nm, 25nm and 50nm. This sets goal is to increase voltages using the large band gap properties of Al_2O_3 . Using the energy band differences between Al_2O_3 and Ge it appeared possible to increase the overall V_{oc} . As shown, although the voltage did increase, it did not increase nearly as much as hoped. This trial did, however introduce the idea of encapsulating the junction as a means to force a favorable reaction between Ge and GeTe discussed more in Section 5.3. The resultant barrier change for set 6 with respect to set 2 is: 127mV, 126mV and 109mV. With measured V_{oc} differences of: 9.8mV, -26.2mV and -51mV for samples 6A-6C respectively. The goal of this set was successful in almost doubling the measured V_{oc} under illumination.

The intent of sample set 7 is to determine an optimum thickness of GeTe to be used in future devices. An initial value of 200nm was selected as it is thick enough to have significant impact at almost half the thickness of the substrate. In order to assess if the thickness of this layer should change, thickness variations were tested ranging from thicknesses of: 10nm, 50nm and 30nm for samples 7A-7C respectively. This progression was meant to be linear, however due to initial characterization tests, samples 7B and 7C were switched resulting in the non incremental layer thicknesses displayed on Table 3. All 3 samples have a uniform 50nm layer of Al_2O_3 which results in the following calculated and measured values with respect to set 2. Calculated barriers for set 7 resulted in a net change from set 2 of: 123mV, 48mV and 47mV. This also produced the measured V_{oc} changes of: -57.9mV, 21.1mV and -50.3mV. This indicates that sample 7A, with an increase of 57.9mV for measured V_{oc} when compared to sample 2A, having the thinnest of GeTe layers improved the most in terms of measured voltages on the solar simulator. This clearly indicates that the

thickness of GeTe is significantly imposing on the device V_{oc} values. However, similar to set 6, the effects of encapsulating the GeTe on this sample set were not investigated and may have played a more significant role.

Since all samples 2-7 were activated at 400°C the question into temperature dependence needed to be addressed. In order to investigate this issue, samples 9A-C were created identically up to the activation step. At this step they were each annealed for incrementally longer times at 250°C. When compared to set 2, the samples annealed for 1, 2 and 3 hours showed the following change in calculated barrier heights of: 129mV, 81.4mV and 78.9mV. These resulted in measured V_{oc} differences of: -21.4mV, -104.7mV and -74.8mV. This is indicating that a lower temperature for longer duration may be more beneficial to junction formation. Similar to sets 6 and 7, the possibility of encapsulation having an impact on performance was not investigated with this set. For sample set 9, the change in calculated barrier voltages directly followed the measured voltages from the solar simulator.

Sample sets 10 and 11 were designed for comparison between each other, however comparing them to sample set 2 have results similar to that of set 7's comparison to set 2. Both 10A-B and 11A-B were created with 10nm GeTe and 100nm Al_2O_3 . The "A" samples were compared both to each other and to their counterpart "B" samples. In doing this, comparing the "A" and "B" sample barrier heights had an average change of -44mV and -156mV respectively. Comparing within their own set, set 10 and 11 had net changes of -40mV and -1mV. These two comparisons show that concerning barrier heights, set 11 had a greater average change compared to set 10, with most of the change occurring with the shorter duration anneal, the A samples. This shows that the use of an encapsulating layer is indeed effective for the activation of the junction up to a couple of hours for Al_2O_3 . This also results in differences from

set 2 of: -7.6mV, 35.4mV, -50.4mV and -43.8mV respectively. Sample 10A was very similar to, but slightly better than sample 2A, which was mostly expected, though the lower temperature appears to have formed a slightly better PN-junction.

5.3 Annealing Effects

As expected, annealing plays a key role in forming PN-junctions. Because of this fact, only two variations were tested in order to assess the effects other variable changes as shown in Table 1. The junction formation assumptions in the analysis completed in Section 5.2 assume total ionization of impurity concentrations in n-Ge and GeTe. Since lower than predicted V_{oc} were measured in samples, the question must be brought up as to why this is lower. The most likely cause is to assume that the ideal case did not occur and not all impurities reacted as planned. Since all samples were annealed at atmosphere at relatively high temperatures, it is possible that Ge and Te reacted with oxygen instead of other donors. However, this possibility was not investigated. Another possibility, that was investigated, is related to findings by other researchers indicating that a breakdown of GeTe may have occurred allowing formation of metallic sections of Ge_2 and Te_2 . This has been observed at 400°C in studies on the effects of long anneal times on GeTe [51]. It was because of this possibility that samples 10 and 11 were created. These samples were designed such that the only difference between the two was the application of an encapsulation layer on set 11 that is not present on set 10, during annealing steps of processing. As shown in Table 1,3 and 4, the samples were designed to be physically as close to identical as possible. Annealing the two sets for different durations was meant to determine the effectiveness of encapsulation in preventing out diffusion over time. A summary of the results from EDAX images and analysis of these two sample sets are shown in Table H-4 with complete results listed in Appendix C.

5.4 Scanning Electron Microscope and Energy Dispersive X-Ray Diffraction Analysis

In order to better understand the composition of samples, SEM and EDAX scans were performed on samples 10A and 11A. The choice to limit scans to only these two samples was due to equipment overheating during the scans. This resulted in significant downtime in order to prevent total equipment failure. Using Equation (19) and assuming the dispersion profile shown in Figure 23, the known densities and energy levels of Ge and Te were used to determine an X-ray escape depth of approximately 1.3 μ m for a 2keV beam. This energy of 2keV was selected as it is the minimum energy available on the test equipment that would have the ability to detect both Ge and Te. With such a large penetration depth compared to the small amount of Te, total volume percentages were dependent upon the beam size and focus. Because of this, care was taken to keep from adjusting these parameters after they were set. As expected, significant percentages of Nitrogen (N_2) were detected in sample 11A that were not present in 10A due to the encapsulation layer. While this did appear to impact data collected from scans for Ge, it did not appear to impact the determination of the Te content. Based on these trials, it is indeed likely that at temperatures of, and greater than, 250°C, Te is separating entirely from GeTe. This adds support to sample sets 6,7 and 9 in their overall performance success compared to sample set 2. Based on the times used to anneal these samples, this out diffusion is not fully inhibited by the encapsulation layer. It was observed that at anneal times for two hours, the out diffusion appears to have still occurred up to an apparent equilibrium point. However this was not verified using EDAX or any other test means. Multiple points were selected for scanning with SEM and EDAX analysis. Some of the points in the scans for sample 11A were placed on dark regions found throughout the sample. These regions appear to be high in N_2 and were excluded in the summary table as

the goal was to compare percentages of like regions. Without this exclusion of test points, the regions under test still show that the measured content of Te remained higher in the encapsulated than in non-encapsulated samples.

Samples in which the GeTe was encapsulated during annealing had much higher percentages of Te, and had performance voltages that were closer to predicted values. This indicates that Te out diffusion is indeed an issue for both RTA and junction activation temperatures as indicated in comparison between sets 6/7 and sets 2-5 in which the former are encapsulated with Al_2O_3 and the latter are not. Samples 2-7 were all activated at 400°C and RTA'd at 640°C . Using the approximate remaining dopant concentrations calculated using Figure 13 the peak approximated percent ionized was for sample 9B at 15%. Sample set 11 is more consistent with both finger up and down values ranging between 2-8% have greater performances than any of the non-encapsulated samples tested. All sample calculations for N_a are shown in Table H-6 with the averaged percent ionized shown.

5.5 Layer Orientation

Samples were layered in a manner to best solicit the optical properties of the materials as well as aide in processing and junction formation. Since all films are thin films, it was suspected that the overall orientation had little impact on junction properties. This was confirmed in Table H-8 and Table H-5, with all values only off by tens of millivolts. Although layer orientation of these thin film materials appears to have had little affect on barrier voltage, as shown in Section 5.3 they did significantly impact the material composition of GeTe after thermal processing. Although it did appear to limit out diffusion, the possibility that this was helping or preventing activation of dopants was not clear and left to future work discussed in Chapter VI.

5.6 Contact Forming

It is well known that making ohmic contacts to n-type Ge can be quite challenging. Due to this, previous works [37],[52] indicated that the application of a thin Al_2O_3 layer before contact depositions would allow adequate bonding of Al to n-type Ge. Because of this all samples had a 3nm layer of Al_2O_3 deposited to pin the Fermi-level [53] allowing for the creation of an ohmic contact. This method resulted in consistent contacts formed using Al and Au.

5.7 Generation And Recombination

As described in Chapter II, the generation of electron hole pairs and the recombination of the same can dramatically affect the overall net current produced from a solar cell. All samples indicated an overall net generation of electrons which is expected for a useful power producing device. The overall calculated rate, was quite high as expected for Ge, Table H-7. The positive valued rate indicates that these devices are recombination dominant [11], which may be another factor in the lower than expected V_{oc} .

The reason behind this phenomena points to the fact that GeTe is an intrinsic material and very similar in band energy to Ge. Because of this, the majority of recombination traps and the conduction band are in very close proximity. Although the generation of electrons is quite rapid, due to this close proximity between conduction and trap bands, it is just as easy for recombination to occur, bringing those generated electrons back to a relaxed state. This may be the reason in the lower current densities observed during testing.

5.8 Reflectance and Transmission

Looking at the transmittance reveals that all samples did have a junction formed that is absorbing energy within the 800-1700nm range. The most common deviation observed from this range of absorption was seen at the fringes of this range. Some samples, namely in sample sets 2,3,7,11 showed a wider absorption of light from 400-1800nm. Transmission percentages increased over 1800nm as anticipated since the wavelength is too small to be absorbed as energy, however absorption is still occurring likely contributing to the increase in sample temperature.

The two samples that performed the best during solar simulator tests, set 7 and 11, had essentially zero transmittance from 400-1800nm indicating both had a strong junction formation. Interestingly, set 9 performed well on solar simulator tests, but appeared to be less responsive during reflectance and transmittance, having a more uniform response across the spectrum. This appears to be due to the outer layer of Al_2O_3 but no further investigations into this phenomena were pursued.

VI. Conclusions and Future Work

6.1 Conclusions

Development of a new type of photovoltaic device previously unattained has been proven possible using basic Micro-Electro-Mechanical Systems (MEMS) processing procedures. It was discovered that the key to forming this junction lies in the encapsulation and controlled reaction of GeTe with Ge. Evidence suggests that a thin capping layer, approximately 100nm, of Al_2O_3 or Si_3N_4 are both effective in a limited capacity at maintaining the Ge to Te ratios during thermal processes. The ability to form this junction at lower temperatures, around the first crystallization temperature of GeTe may prove useful as well to future endeavors. The low values obtained for this device are suspected to stem from low ionization of atoms creating a small depleted region for use in creating electron-hole pairs. The source of deficiency within this region could be due to many factors, of which only loss of Te was pursued.

Further investigations into this device structure are imperative in order to improve performance and refine processing steps. Further testing of initial assumptions should also be completed and refined as this viable option to improve or replace existing technologies remains largely unexplored in this capacity. Since test parameters for this technology were designed to probe the potential of the technology rather than investigating one solution in-depth, the true potential of the Ge/GeTe photovoltaic cell remains largely untapped. In the growing need to reduce carbon footprints, by expanding available renewable power generation solutions, no technology that shows potential can be overlooked.

6.2 Future Works

While extensive research has been accomplished involving the formation and testing of a Ge\GeTe junction, certain phenomena, such as recombination, lattice constants, etc., were assumed to have no to little effect on the overall process. After analysis, some of these assumptions may have been invalid requiring further attention. They are listed in this section as areas of consideration for future endeavors.

6.2.1 Capping Effects.

During processing, lower than expected results were observed. Even though samples were processed at low temperatures, samples exhibited similar elemental breakdown found in other research [51]. During data analysis, it was shown that application of a cap layer to the GeTe surface during junction activation and RTA allowed for a maintained GeTe:Ge ratio. While this appeared to aide in junction formation, it is unclear if another junction between GeTe and the cap layer was created. Such a junction, or other reaction with the cap layer, could have been one reason for the still lower than anticipated V_{oc} values. Further research into junction formation between GeTe and Si_3N_4 , Al_2O_3 and other possible cap materials would further improve understanding of GeTe interactions during annealing processes. In situ testing of thinly capped GeTe during annealing would also enable a much greater understanding of ChG material properties.

6.2.2 Recombination Effects.

The effects of generation and recombination of majority and minority carriers are critical to an effective device. As it was discussed in Chapter V, Section 5.7, the calculated rates proposed during this study were acceptable for device operation,

however, there are other effects that were not analyzed. It was suspected that these interactions occurred relatively close to trap energy levels, greatly reducing the carrier lifetime from that which was predicted. Investigation of the trap energy levels created during this device creation could greatly aid in further understanding of this device structure, leading to more effective devices.

6.2.3 Other Considerations.

Other considerations in using Sb doped Ge and GeTe for device creation is the reaction between Sb and GeTe. The possibility that these interactions could be forming a device similar to one created using un-doped Ge and Germanium Antimony Telluride (GST). The possibility of this sort of interaction was not investigated. Possibly outcomes could lead to less costly, easier and more controlled creation procedures. It could also have applications allowing for creation of micro level thin film solar cells through use of co-sputtered Ge and GST embedded into MEMS devices.

Other materials considered during initial device testing included Vanadium Oxide (V_xO_y) as a hole injection layer, means to increase the band gap response, increase built in voltage, and shift recombination traps away from the mid-gap. Due to lack of time to properly characterize the controlled deposition of this material using the available equipment, this endeavor was not pursued.

Appendix A. MATLAB Code

A-1 MATLAB Functions

This section lists methods created for use in other scripts.

A-1.1 plotSolarSimData.m.

```
function [tdD,tdU] = plotSolarSimData(filnames, barriers, procTemp)
vt = 0.0259; E = exist('procTemp','var');
if (E==0)
    procTemp = 300;          %in Kelven
end
A1 = GeGeTe(0.72,0.1212,procTemp);
tdD = table2cell(readtable('SolarSimulatorData(FingerDown).xls'));
tdU = table2cell(readtable('SolarSimulatorData(FingerUp).xls'));
%Measured Voc for samples on solar simulator
%col1 = ID, col2=voc, col3 = isc
tdD = tdD(:,1:3); tdU = tdU(:,1:3);
for k = 1:size(tdD,1)
    %finger down values
    voc1 = str2double(cell2mat(tdD(k,2)))*1e-3;
    isc1 = str2double(cell2mat(tdD(k,3)))*1e-6;
    ssN(k,:) = (1/vt)*(voc1/log(isc1));
    %solar simulator rev current
    ssJ(k,:) = isc1/(exp(-voc1./vt)-1);
    %calc'd barrier for solar simulator point
    ssphi(k,:) =real(-vt*log(ssJ(k,:)./(ssN(k,：)*A1.Nd)));
    %finger up values
    voc2 = str2double(cell2mat(tdU(k,2)))*1e-3;
    isc2 = str2double(cell2mat(tdU(k,3)))*1e-6;
    ssN2(k,:) = (1/vt)*(voc2/log(isc2));
    %solar simulator rev current
    ssJ2(k,:) = isc2/(exp(-voc2./vt)-1);
    %calc'd barrier for solar simulator point
    ssphi2(k,:) = real(-vt*log(ssJ2(k,:)./(ssN2(k,：)*A1.Nd)));
end
phiend = num2cell(double(barriers.'));
%%
```

```

hrd = [cellstr('Sample_ID'),cellstr('Barrier_Volts')];
DiodeTestTable=cell2table([filnames;phiend].',' , 'VariableNames',hrd);
hrd = [cellstr('Sample_ID'),cellstr('Barrier_Finger_Down_Volts'),cellstr('
    Barrier_Fingers_Up_Volts')];
SolarSimTable=cell2table([tdD(:,1),num2cell(ssphi),num2cell(ssphi2)], 'VariableNames',
    hrd);
% writetable(SolarSimTable,'Table Save Location and Name');
% writetable(DiodeTestTable,'Table Save Location and Name');
%% Plot Solar Simulator Data
figure();
set(gcf, 'Position', get(0,'Screensize')); % Maximize figure.
hold on
bar([ssphi2,ssphi]); H = gca; H.XTick = 1:size(tdD,1); H.XTickLabel = tdD(:,1);
title('Calculated barrier voltage from Solar Simulator')
xlabel('Sample ID'); ylabel('Calculated Barrier Voltage (V)');
legend('Finger Pattern Up','Finger Pattern Down')
% fname = 'Solar_Simulator_Calculated_Junction_Voltages';
% saveas(gcf,[fpath,fname], 'jpeg');% close all;
end

```

A-1.2 GeGeTe.m.

```

function S = GeGeTe(rohp,rohn,T)
%% Constants
Et = 3.9; %Trap energy level in eV k = 1.3806e-23; %eV/K
E = exist('T','var');
if (E==0)
    T = 300; %in Kelven
end
q = 1.602e-19; mup = 1900; mun = 3900; mupp = 120; munn = 120;
m = 9.10138356e-31; ev = 8.854e-14; er = 16; err = 37.5; %permittivity of GeTe
esn = ev*er; esp = ev*err; ni = 2.4e13; nigt = 3e20;
%effective mass of e & h in Ge
mn = 0.082; mp = 0.044; asmp = 1e10;
%blanket assumption ratio of majority to minority carrier concentrations
dlta = 1e4; %Junction Step size for V sampling
% Calculations 1
ninet = sqrt(ni*nigt); Na = ((q*rohp)*mupp)^(-1); Nd = ((q*rohn)*mun )^(-1);

```

```

Dn = (k*T*mun)/q; Dp = (k*T*mupp)/q; sn = 1/rohn; sp = 1/rohp; vth = sqrt(3*k*T);
taup = ((Na*vth*sp)^(-1))*(sqrt(mp/m)); taun = ((Nd*vth*sn)^(-1))*(sqrt(mn/m));
%% Calculations 2
Phi = (k*T/q)*log((Na*Nd)/(ninet^2));
% Phi = (k*T/q)*log((Nd)/(ninet)); %since GeTe Intrinsic, Phi_i = Phi_n
lp = sqrt((2*esn/q)*((Phi*Nd)/(Na*(Na+Nd))));
ln = sqrt((2*esp*(1/(2e-4*16))/q)*((Phi*Na)/(Nd*(Na+Nd))));
lp = sqrt(real(lp)^2+imag(lp)^2); ln = sqrt(real(ln)^2+imag(ln)^2);
Js = q*(ninet^2)*(((Na)^(-1)*sqrt(Dn/taun))+((Nd)^(-1)*sqrt(Dp/taup)));
% js = sqrt((q^2)*(k*T/q)*mupp*(ni^2/Nd)*(rohn/(vth/sqrt(mn))));
J = Js*(exp((q*Phi)/(k*T))-1); Emax = -ln*q*Nd/esp;
%solar cell generation rate
dn = 0:ln/dlta:ln; dp = -lp:lp/dlta:0;
a = (q/(2*esn))*((Na*dp.^2)+(Nd*dn.^2));
j = Js*diff((q/(k*T))*a,1)*exp((q*Phi)/(k*T));
% Generation/recombination rate assuming Et-Ei ~ Ec
U = ((Na*Nd)-(ninet^2))/(max(taun,taup)*(Na+Nd+(2*ninet*cosh(((Et-4.35)*q)/(k*T)))));
%package data for use
VI = ((q*Na*lp^2)/2)*((1/esp)+(Na/(esn*Nd)));
B = sqrt(Phi^2+VI^2); % avg between hetero and homo built in voltages
S = struct('Vbi',B,'J',J,'Vmax',Emax,'Tn', ...
    taun,'Tp',taup,'Wn',ln,'Wp',lp,'Urg',U,'volts',a(1:end-1),'amps',j,...
    'Diffusion_Ge',Dn,'Diffusion_GeTe',Dp,'Is',Js,'Na',Na,'Nd',Nd);
end

```

A-1.3 TestCode.m.

```

function [V,I] = TestCode(list,ax,p)
E = exist('p','var');
if (E==0)
    p = false;
end
if(p)
    H=figure(1); fsiz = 32; lwid = 2;
    sty={'--o','-',':','--+', '-. ','--','--^','--d','--v','--s','-->'};
end
E = exist('ax','var');
if (E ~= 0)

```

```

        p = true;
    else
        if(p)
            axis([-10 10 -0.1 0.1]);
        end
    end
end
if (p)
    hold on; set(gca, 'LineStyleOrder', sty); set(gcf, 'Position', get(0, 'Screensize'))
    ;
end
E = exist('list', 'var');
if (E == 0)
    list = dir('*.txt'); list = {list.name}.'; [x,~] = size(list);
    for k = 1:x
        D = parsetxt(char(list(k,:)));
        V(k) = D(1,:); I(k) = D(2,:); plot(D(1,:), D(2,:), 'LineWidth', lwid);
    end
    legend(list, 'Location', 'best');
else
    if(isstruct(list))
        data = struct2cell(list); data = data(1,:).'; [x,~] = size(data);
        for k = 1:x
            D = parsetxt(char(cell2mat(data(k)))));
            V(k,:) = D(1,:); I(k,:) = D(2,:);
            if(p)
                plot(D(1,:), D(2,:), 'LineWidth', lwid);
            end
        end
        if(p)
            legend(data, 'Location', 'best');
        end
    end
end
if (p)
    ylabel('Current (Amps)'); xlabel('Voltage (Volts)');
end end

```

A-1.4 plotDiodeData.m.

```

function [afil,phiend,voc,Urg1] = plotDiodeData(samples,procTemp)
rng = []; Urg =[]; Urg1 =[]; afil = []; jfil = [];
voc = []; phiend = []; bgraph = []; ctr = 0; vt = 0.0259;
fpath = 'Image Save Location';
sty={'-','--',':', '-.-','--+', '--<','--o'};
fsiz = 14; lwid = 1.5; E = exist('procTemp','var');
if (E==0)
    procTemp = 300;          %in Kelvin
end
A1 = GeGeTe(0.72,0.1212,procTemp); ninet = 2.4e13;%
for KK = 1:length(samples)
    nam = ['S-',cell2mat(samples(1,KK)), '*.txt'];
    dat = dir(nam); dat2 = struct2cell(dat); files = dat2(1,:);
    afil = [afil,files]; figure()
    %Trim file names for display on graphs
    for u = 1:length(files)
        fu = strrep(cell2mat(files(1,u)),'.txt','');
        fu = strrep(fu,'N-NC','C'); nfil(u,:) = mat2cell(fu.',length(fu));
    end
    %determine values for each file(sample iteration)
    for k = length(files)-1:length(files)
        %load Diode Test data from file
        fil = char(files(1,k)); [v,ij] = TestCode(dir(fil));
        %determine ideality factor
        for n = 1:(length(v)-1)
            %ideal factor for each point
            NN(k,n) = (1/vt)*((v(n+1)-v(n))./(log(ij(n+1)./ij(n))));
            if (~isfinite(NN(k,n)))%filter "INF" values
                NN(k,n) = 0;
            end
        end
        nmax = max(max(NN));
    %set "INF" values to maximum readable value for display purposes
    for n = 1:length(NN)
        if (NN(k,n) == 0)
            NN(k,n) = nmax;
        end
    end
    %avg ideality factor for each sample

```

```

    N(1,k) = mean(abs(log(NN(k,:))));
%calc'd barrier for each point
    phi(k,:) = -vt*log(ij./(exp(-v./vt)-1)*N(1,k)*A1.Nd);
%remove infinite or NaN values
    while (~isfinite(min(phi(k,:))))
        [~,z] = min(phi(k,:));
        if ((z>1) && isfinite(phi(k,z-1)) && isfinite(phi(k,z+1)))
            phi(k,z) =(phi(k,z-1) + phi(k,z+1))/2;
        else
            phi(k,z) = 0;
        end
    end
    while (~isfinite(max(phi(k,:))))
        [~,z] = max(phi(k,:));
        if ((z>1) && isfinite(phi(k,z-1)) && isfinite(phi(k,z+1)))
            phi(k,z) =(phi(k,z-1) + phi(k,z+1))/2;
        else
            phi(k,z) = 0;
        end
    end
    temp = max(phi(k,:));
    for u = 1:length(phi(k,:))
        if (phi(k,u)==single(0))
            phi(k,u) = temp;
        end
    end
    phia(k,1) = log(mean(phi(k,:)));%average barrier value for each sample
    phib(k,1) = max(phi(k,:))-min(phi(k,:));% barrier delta for each sample
    vo(k,:) = real(vt*log((ij./A1.Is)+1)); U1(k,:) = ij - A1.Is*(exp(v./vt)-1);
    U(k,:) = ((ninet^2)*(exp(v./vt)-1))/(A1.Tp*(A1.Na+A1.Nd+(2*ninet)));
end
x = size(phi,1);
hold on; w = gca; w.LineStyleOrder = sty; w.LineWidth = lwid;
%w.ColorOrder = [0 0 0];
w.ColorOrder = [0 0.4470 0.7410;0.9290 0.6940 0.1250;0.6350 0.0780 0.1840];
w.XLim = [-10 10]; figure(KK) hold on;
for h = 1:x
    plot(v,real(phi(h,:))); ctr = ctr +1; indx = find(v==0);
    if (h == x)
        bgraph = [bgraph;real(phi(:,indx))];
    end
end

```

```

        end
    end
    xlabel('Applied Voltage'); ylabel('Calculated Barrier Voltage');
    legend(nfil,'Location','Best') figure(KK+length(samples)) hold on;
    for h = 1:x
        %plot(ij,real(vo(h,:)));
        plot(v,ij);
    end
    ylabel('Measured Current'); xlabel('Measured Voltage');
    legend(nfil,'Location','Best')
    fname = ['SampleSet_',cell2mat(samples(1,KK)),'Calculated_Junction'];
    %saveas(gcf,[fpath,fname],'jpeg');
    %close all;
    phiend = [phiend;phib]; voc = [voc;vo]; Urg = [Urg;U]; Urg1 = [Urg1;U1];
    rng = [rng,nfil.']; clear phib; clear vo; clear U; clear U1; clear nfil;
    clear phi; end end

```

A-2 MATLAB Scripts

This section contains the main scripts that were run in order to produce and save data plots.

A-2.1 ModelToDataCompare.m.

```
close all; clear; procTemp = 300; S1 = GeGeTe(0.72,0.1212,procTemp);
vt = 0.0259; nigt = 8e20; q = 1.602e-19; ni = 2.4e13;
%% Diode Test Data Calculations
samples = {'2','3','5','6','7','9','10','11'};
[bnames,barriers,vocs,U] = plotDiodeData(samples,procTemp);
close all;
%% Load and Calculate Solar Sim Test data
[td,tu] = plotSolarSimData(bnames,barriers,procTemp);
%% plot vocs
for u = 1:length(bnames)
%cleanup file names for use
    fu = strrep(cell2mat(bnames(1,u)),'.txt','');
    fu = strrep(fu,'S-',''); fu = strrep(fu,'-NC','');
    fu = strrep(fu,'-OAN',''); fu = strrep(fu,'-1AN','');
    fu = strrep(fu,'-2AN',''); fu = strrep(fu,'-3AN','');
    fu = strrep(fu,'-4AN',''); nfil(1,u) = mat2cell(fu.',length(fu));
end
figure() set(gcf, 'Position', get(0,'Screensize')); hold on;
plot(1:length(nfil),mean(vocs.')) H = gca; H.XTick = 1:length(mean(vocs.'));
H.XTickLabel = cell(nfil,1);
xlabel('Sample ID'); ylabel('Calculated Barrier Voltage (V)');
Va = double(mean(vocs.')); close all;
for jj = 1:size(td,1)
    mV = str2double(cell2mat(tu(jj,2)))*1e-3;
    NAu(jj,1) = S1.Na-(exp(mV/vt)*(2.4e13)*(nigt)/(S1.Nd));
    mV = str2double(cell2mat(td(jj,2)))*1e-3;
    NAd(jj,1) = S1.Na-(exp(mV/vt)*(2.4e13)*(nigt)/(S1.Nd));
end
NaTab = [td(:,1),num2cell(NAu(:,1)),num2cell(NAd(:,1))];
NaTab = [{'Sample_ID','Na_Up','Na_Dn'};NaTab];
for jj = 2:size(NaTab,1)
```

```

    pctA = (cell2mat(NaTab(jj,2))/nigt); pctB = (cell2mat(NaTab(jj,3))/nigt);
    pctchg(jj,1) = num2cell(pctA); pctchg(jj,2) = num2cell(pctB);
    pctchg(jj,3) = num2cell(mean([pctA,pctB]));
end
pctchg(1,:) = {'Pct_Na_Remaining'}; NaTab = [NaTab,pctchg(:,3)];
NaTable = cell2table(NaTab(2:end,:), 'VariableNames', NaTab(1,1:end));
for kk = 1:size(U,1)
    idx = 0;
    for jj = 1:size(U,2)
        if(isfinite(U(kk,jj)))
            idx = idx + 1; U2(idx) = U(kk,jj);
        end
    end
    U3(kk,1) = mean(U2); clear U2;
end
for u = 1:length(bnames)
    fu = strrep(cell2mat(bnames(1,u)),'.txt','');
    fu = strrep(fu,'N-NC','C'); fu = strrep(fu,'-','');
    fu = strrep(fu,'S',''); bnames2(1,u) = cellstr(fu);
end
RecRate = [bnames2.',num2cell(U3)];
RecRate2 = ... cell2table(RecRate, 'VariableNames', {'Sample_ID', 'Recombination_Rate'})
;
%writetable(RecRate2,'Table Save Location');
figure() w = gca; hold on;
for jj = 1:size(U,1)
    plot(vocs(jj,:),U(jj,:))
end
xlabel('Voc'); ylabel('Recomb/Gen Rate');
w.YLim = [min(min(U)),abs(max(max(U)))];
w.XLim = [min(min(vocs)),abs(max(max(vocs)))];
close all;

```

A-2.2 PlotBuilder.m.

```

close all; clear; lnames = []; sty={'-','--',':', '--o'}; fsiz = 24; lwid = 1.5;
names = {'S-2*','S-3*','S-5*','S-6*','S-7*','S-9*','S-10*','S-11*'};
fname ={'S_2','S_3','S_5','S_6','S_7','S_9','S_10','S_11'};

```

```

fpath = 'Save Location1';
d = 'Image Save Location'; figure() w = gca;
w.LineStyleOrder = sty; w.LineWidth = lwid; w.FontSize = fsiz;
for k = 1:length(names)
    hold on fil = cell2mat(names(k,1)); lst = dir(fil);
    TestCode(lst,[-10 10 -0.11 0.11],true);
    %saveas(gcf,[d,cell2mat(fname(k,1))],'jpeg');
    au = struct2cell(lst);
    for hg = 1:size(au,2)
        clear fu; fu = strrep(cell2mat(au(1,hg)),'.txt','');
        fu = strrep(fu,'-NC',''); fu = strrep(fu,'AN','');
        fu = strrep(fu,'-',''); fu = strrep(fu,'S','');
        fu = fu(1,1:end-1); lnames = [lnames;cellstr(fu)];
    end
end
legend(lnames,'Location','best');

```

A-2.3 IVPlotter.m.

```

clear; close all;
%% Get Reflectance Data for samples
samples = {'2','3','5','6','7','9','10','11'};
sty={'-','-',':','--o'}; fsiz = 24; lwid = 1.5; zlist = {};
a = 2; b = 2; Y = 0; Z=0; X = [400 2400]; ctr = 0;
fpath = 'Image Save Location'; pat = 'Reflectance Data Location';
pat2 = 'Absorbance Data Location';
for ii = 1:length(samples)
    rng = [cell2mat(samples(ii)),'*'];
    fname = ['SampleSet_',rng(1:end-1),'_RefTrans'];
    wholePath = [pat,'Ge_GeTe_',rng,'.csv'];
    wholePath2 = [pat2,'Ge_GeTe_Absorb_',rng,'.csv'];
    dat = dir(wholePath); dat2 = struct2cell(dat); clear dat;
    files = dat2(1,:).';
    for x = 1:length(files)
        ctr = ctr+1; fnam = [pat,char(files(x))];
        data2 = readtable(fnam); lam = table2array(data2(:,1));
        pctR = table2array(data2(:,2)); [m,~] = find(lam==2400);
        lam = lam(m:end,1); pctR = pctR(m:end,1);
    end
end

```

```

        list = dir(wholePath); list = {list.name}.';
        list = strrep(list,'Ge-GeTe-', ''); list = strrep(list, '.csv', '');
        Rfs(ctr,2) = num2cell(mean(pctR)); Rfs(ctr,1) = list(x);
    end
end

%% Plot IV data
scaler = 1e-3; unts = 'W'; acc = 10; tpwr = 1000;
pat = 'Test Data Location'; fil = 'Final_IV_All_Samples.xls'; fnam = [pat,fil];
%%-Read data collected for IV Curve plots
data = readtable(fnam); IDs = table2cell(data(:,1));
V = abs(table2array(data(:,6:2:size(data,2))));
I = abs(table2array(data(:,7:2:size(data,2))));
V = [V,zeros(size(V,1),1)]; V = [table2array(data(:,4)),V]; V = scaler*V;
I = [I,table2array(data(:,5))]; I = [zeros(size(I,1),1),I]; I = (scaler^2)*I;
fil = 'SolarSimulatorData(FingerUp).xls'; fnam = [pat,fil];
data2 = readtable(fnam);
for L = 1:size(I,1)
    plotTitle = cell2mat(IDs(L)); Isc = I(L,end); Voc = V(L,1);
    P = V(L,:).*I(L,:); [~, index] = max(P(:)); Loc = ind2sub(size(P,1),index);
    Impp = I(L,Loc); Vmpp = V(L,Loc); VMpp = [Vmpp, Impp]; Pmax = Impp*Vmpp;
    Pideal = Isc*Voc; FF = Pmax/Pideal; Pin = tpwr*1e-4;
    pctR = cell2mat(Rfs(L,2))/100; Pin = Pin*(1-pctR);
    n(L,1) = round(100*(FF*Pideal/Pin),acc); Pm(L,1) = Pmax; Pi(L,1) = Pideal;
    ff(L,1) = FF; H = figure(); set(gcf, 'Position', get(0,'Screensize'));
    co=[0 0 0];
    sty={'-', '-.', '--', '--+', ':', '--x', '--o', '--<', '--*', '--s', '-->'};
    axes1 = axes('Parent',H,'YGrid','on','XGrid','on',...
        'LineStyleOrder',sty,'ColorOrder',co,'FontSize',38,...
        'FontName','Times New Roman'); hold on; grid off; plot(V(L,:),I(L,:));
    VocX = [Voc, Voc]; VocY = [0, Isc]; IscX = [Isc, Isc]; IscY = [0, Voc];
    plot(VocX,VocY,'--','Color','k'); plot(IscY,IscX,'--','Color','k');
    plot(Voc,Isc,'.','MarkerSize',14,'Color','k'); Vmpp_X = [Vmpp, Vmpp];
    Vmpp_Y = [0, Impp]; Impp_X = [Impp, Impp]; Impp_Y = [0, Vmpp];
    plot(Vmpp_X,Vmpp_Y,'-.','Color','b'); plot(Impp_Y,Impp_X,'-.','Color','b');
    plot(Vmpp,Impp,'.','MarkerSize',14,'Color','b');
    axis([0 (Voc*1.1) 0 (Isc*1.1)]);
    xlabel('Voltage (V)'); ylabel('Curent (A)');
    values = {[ 'Pmax = ',num2str(round(Pmax,acc)),unts]
        [ 'Pideal = ',num2str(round(Pideal,acc)),unts]
        [ 'FF = ',num2str(round(100*FF,acc)), '%']}

```

```

    ['Eff. = ', num2str(n(L,1)), '%'];
    legend(values, 'location', 'best');
    fname = ['Sample_', plotTitle, '_IVCurve_Plot'];
    %saveas(gcf,[fpath,fname], 'jpeg');    %close all;
end

```

A-2.4 PlotReflectanceAbsorbance.m.

```

%% Plot Reflectance
samples = {'2','3','5','6','7','9','10','11'};
%samples = {'6'};
sty={'-','--',':', '--o'};
fsiz = 14; lwid = 1.5; flist = [];
    %samples to plot data for
a = 2; b = 2; Y = 0; X = [400 2400];
fpath = 'SavePath';
pat = 'PathToReflectanceDataFiles'; pat2 = 'PathToAbsorbanceDataFiles';
for ii = 1:length(samples)
    rng = [cell2mat(samples(ii)), '*'];
    fname = ['SampleSet_', rng(1:end-1), '_RefTrans'];
    subplot(a,b,1); hold on; w = gca; w.XLim = X;
    w.LineStyleOrder = sty;
    co = [0 0.4470 0.7410; 0.8500 0.3250 0.0980; 0.4940 0.1840 0.5560;
          0.6350 0.0780 0.1840];
    set(groot, 'defaultAxesColorOrder', co)
    w.LineWidth = lwid; w.FontSize = fsiz; wholePath = [pat, 'Ge_GeTe_', rng, '.csv'];
    wholePath2 = [pat2, 'Ge_GeTe_Absorb_', rng, '.csv'];
    dat = dir(wholePath); dat2 = struct2cell(dat); clear dat; files = dat2(1,:).';
    for x = 1:length(files)
        fnam = [pat, char(files(x))]; data2 = readtable(fnam);
        lam = table2array(data2(:,1)); pctR = table2array(data2(:,2));
        [m,~] = find(lam==2400); lam = lam(m:end,1);
        pctR = pctR(m:end,1); plot(lam, pctR, 'LineWidth', lwid); temp = max(pctR);
        if (temp > Y)
            Y = temp;
        end
    end
end
xlabel('Wavelength(nm)'); ylabel('Reflectance(%)'); w.YLim = [0 Y];

```

```

%% Plot Transmittance
subplot(a,b,2); hold on; w = gca; w.XLim = X; w.LineStyleOrder = sty;
co = [0 0.4470 0.7410; 0.8500 0.3250 0.0980; 0.4940 0.1840 0.5560;
      0.6350 0.0780 0.1840];
set(groot,'defaultAxesColorOrder',co)
w.LineWidth = lwid; w.FontSize = fsiz;
dat = dir(wholePath2); dat2 = struct2cell(dat); files = dat2(1,:).';
for x = 1:length(files)
    fnam = [pat2,char(files(x))]; data2 = readtable(fnam);
    lam = table2array(data2(:,1)); absb = table2array(data2(:,2));
    [m,~] = find(lam==2400); lam = lam(m:end,1);%nm
    pctT = 10.^(2-absb(m:end,1));
    plot(lam,pctT,'LineWidth',lwid); temp = max(pctT);
    if (temp > Y)
        Y = temp;
    end
end
xlabel('Wavelength(nm)'); ylabel('Transmittance(%)'); w.YLim = [0 Y];
%%Plot Absorbance
subplot(a,b,3); hold on; w = gca; w.XLim = X; w.LineStyleOrder = sty;
co = [0 0.4470 0.7410; 0.8500 0.3250 0.0980; 0.4940 0.1840 0.5560;
      0.6350 0.0780 0.1840];
set(groot,'defaultAxesColorOrder',co)
w.LineWidth = lwid; w.FontSize = fsiz;
for x = 1:length(files)
    fnam = [pat2,char(files(x))]; data2 = readtable(fnam);
    lam = table2array(data2(:,1)); absb = table2array(data2(:,2));
    [m,~] = find(lam==2400); lam = lam(m:end,1);%nm
    pctT = 10.^(2-absb(m:end,1)); absb2 = 100-pctR-pctT;
    plot(lam,absb2,'LineWidth',lwid); temp = max(absb2);
    if (temp > Y)
        Y = temp;
    end
end
xlabel('Wavelength(nm)'); ylabel('Absorbance(%)');
w = gca; w.YLim = [0 Y]; list = dir(wholePath2); list = {list.name}.';
list = strrep(list,'Ge_GeTe_Absorb_', '');
list = strrep(list, '.csv', ''); flist = [flist;list];
%saveas(gcf,[fpath,fname],'jpeg'); %close all;
end

```

```
subplot(a,b,1); legend(flist,'Location','best')  
subplot(a,b,2); legend(flist,'Location','best')  
subplot(a,b,3); legend(flist,'Location','best')
```

Appendix B. Process Followers

B-1 Alumina Inter-facial Layer

Wafer n-Ge	Purpose Ge-GeTe PV Cell	ID 3	Mask None	Process PN Junction Creation	Print Date 5/18/2016
Init.	Process Step			Notes	Date Time
	I. Solvent Clean (by hand) • Turn on hot plate and set to 110°C • 30 sec acetone rinse at 500rpm • 30 sec methanol rinse at 500rpm • 30 sec DI water rinse at 500rpm • Dry with nitrogen on texwipe • 2 min 110°C hot plate bake • Turn off hot plate*			<u>Start Date</u> <u>Start Time</u>	
	II. Oxygen Plasma Etch • Place n-Ge wafer into Asher, polished-side up • Ash the wafers for 5 min at 75W making sure the reflected power is 0. • Remove wafers, turn Asher off, turn off oxygen tank in raceway.				
	III. Pre-Metallization Surface Preparation • DI:BOE (7:1) solution etch for 30 sec • 30 sec DI water rinse • Dry with nitrogen				
	IV. Atomic Layer Deposition • ALD Al2O3 on polished side of n-Ge wafer: A-3nm, B-5nm • Sputter Deposition and Verification • Place n-Ge wafer (polished-side up) with witness sample on load lock plate • Sputter 200nm GeTe (2mins @ 100W RF power) • Verify thickness of GeTe on profilometer. Record value _____				
	V. GeTe Transition to Create c-GeTe • Place Ge in compatible Furnace at 300°C (Polished/GeTe Side UP) for 30mins (if available). If not, use of probe hotplate. • Annotate which heating device used. _____ • Using four point probe measure sheet resistance (ohm/square). Record values. _____ • Multiply by material thickness (in cm) for ohm-cm value. Record value. _____				
	VI. Pre-Contact Diode Testing • Using Parameter Analyzer connect sample to be tested as a diode. • Set measure and Display ranges for +/- 5V and +/-100mA • Test and record results				
	VII. Pre-Contact Junction Testing • If PN junction not formed in step VI skip to VIII. • Place test piece in Solar simulator and illuminate with 1kW/m^2 • Measure open circuit voltage. Record Value. _____ • Measure Short circuit current. Record Value. _____ • If the previous two steps produced values > micro volts/amps use ohmic breakout box to build IV curve to characterize sample. Draw below or on back.				
	VIII. Optical Parameters Using Reflectometer • Measure Reflectance over ~300-2000nm wavelengths • Measure Transmittance over ~300-2000nm wavelengths				

Process Step #2

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(29 Jan 2016)

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Figure B-1. Page 1 of the process follower used during cell fabrication with alumina as an inter-facial layer using germanium and germanium telluride.

Wafer n-Ge	Purpose Ge-GeTe PV Cell	ID 3	Mask Front Solar Contacts	Process Metallization/Contacts	Print Date 5/18/2016
Init.	Process Step			Notes	Date Time
	I. Complete PN Junction Creation Process follower: 3-Ge-GeTe PV Cell_PN Junction Creation.docx			<u>Start Date</u>	
				<u>Start Time</u>	
	II. Solvent Clean (Un-polished Side up) - Turn on hot plate and set to 110°C 30 sec acetone rinse at 500rpm 30 sec methanol rinse at 500rpm 30 sec DI water rinse at 500rpm - Dry with nitrogen on texwipe 2 min 110°C hot plate bake - Turn off hot plate*				
	III. Oxygen Plasma Etch - Place n-Ge wafer into Asher, polished-side up - Ash the wafers for 5 min at 75W making sure the reflected power is 0. Remove wafers, turn Asher off, turn off oxygen tank in raceway.				
	IV. Pre-Metallization Surface Preparation - DI:BOE (7:1) solution etch for 30 sec 30 sec DI water rinse - Dry with nitrogen				
	V. Atomic Layer Deposition ALD 3nm of Al2O3 on unpolished side of n-Ge wafer				
	VI. Metallization Evaporate 5000 Å of Al on unpolished side of n-Ge				
	VII. Photoresist (SF11-for Finger patterning) - Turn on hot plate and set to 200°C - Flood wafer with SF-11 30 sec Spin at 4000 rpm – Hold swab between wafer and Spinner walls to catch excess photoresist (“cotton candy” strands) 2 min bake @ 200°C - Turn off hot plate*				
	VIII. Photoresist(1818- for fingers patterning): - Turn on hot plate and set to 110°C - Place n-Ge wafer (Polished-side up) on spinner - Flood with 1818 photoresist 30 sec spin at 4,000 rpm 1min @ 110°C hot plate bake (shorter time since it'll bake again for metallization protection coat - Turn off hot plate				
	IX. Photoresist: (1818 -to protect metallized side) - Turn on hot plate and set to 110°C - Place n-Ge wafer (Metallized-side up) on spinner - Flood with 1818 photoresist 30 sec spin at 4,000 rpm 2min @ 110°C hot plate bake - Turn off hot plate*				
	X. Clean H-Ring pattern contact mask under solvent hood (by hand) 30 sec acetone rinse 30 sec methanol rinse 30 sec IPA rinse - Dry with nitrogen - Position mask in MJB3 Mask Aligner				

Process Step #2 Revision 0 (9 May 2016)
 *.This step only necessary if starting or stopping mid-process follower

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Figure B-2. Page 2 of the process follower used during cell fabrication with alumina as an inter-facial layer using germanium and germanium telluride.

Wafer n-Ge	Purpose Ge-GeTe PV Cell	ID 3	Mask Front Solar Contacts	Process Metallization/Contacts	Print Date 5/18/2016
	XI. Expose 1818 – H-Pattern Contact Mask • Prior to exposing, wafer is centered under mask as best as possible • Expose wafer using MJB3 contact mask aligner for 8 sec				
	XII. 1818 Develop: • Turn on hot plate and set to 110°C • Place wafer on spinner under Base Hood • 45 sec develop with 351:DI (1:5) developer at 500 rpm • 30 sec DI rinse at 500 rpm • Dry with nitrogen at 500 rpm • Dry wafer with nitrogen on clean tex-wipes • 1 min 110°C hot plate bake (drying) • Turn off hotplate				
	XIII. Expose SF11 • Place wafer in center circle • 300 sec DUV exposure with OAI DUV				
	XIV. SF11 Develop: • Turn on hot plate and set to 110°C • 60 sec bucket develop with SAL 101 • 30 sec DI rinse at 500 rpm • Dry with nitrogen at 500rpm • Dry any remaining water with nitrogen on tex-wipe • 1 min 110°C hot plate bake (drying) • Turn off hotplate*				
	XV. Front Contact Metallization • Evaporate 100Å of Ti / 5000 Å of Au onto c-GeTe side of wafer				
	XVI. Solvent Clean and Lift-off • Heat 1165 remover to 90°C (hot plate at 200°C) • Use packing tape to lift off portion of Au/Ti • 5 min ultrasonic bath in acetone (remove 1818 and un-bonded metal) • 30 sec acetone rinse at 500 rpm • 30 sec isopropyl alcohol rinse at 500 rpm • 30 sec DI water rinse at 500 rpm • Dry with nitrogen at 500 rpm • 5 min soak in 1165 at 90°C • 30 sec DI rinse at 500 rpm • Dry wafer with nitrogen on clean tex-wipes • Turn off hotplate*				
	XVII. Anneal contacts • RTA for 20seconds @ 640°C				

Process Step #2 Revision 0 (9 May 2016)
 *.This step only necessary if starting or stopping mid-process follower

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Figure B-3. Page 3 of the process follower used during cell fabrication with alumina as an inter-facial layer using germanium and germanium telluride.

B-2 Encapsulation Layers

B-2.1 Alumina.

Wafer n-Ge	Purpose GeTe pn-junction	ID 9(A-C)	Mask None	Process PN-Jcn Creation/Metallization	Print Date 11/3/2016
Init.	Process Step			Notes	Date Time
	I. Solvent Clean (by hand) 30 sec acetone rinse 30 sec methanol rinse 30 sec DI water rinse - Dry with nitrogen on texwipe 2 min 110°C hot plate bake*			Start Date Start Time	
	II. Sputter Deposition and Verification - Place n-Ge samples with witness on load lock plate - Load and Sputter 175nm GeTe on Un-polished side - Verify thickness of GeTe on profilometer. Record value _____				
	III. ALD of Al₂O₃ - Deposit 50nm of Al₂O₃ on GeTe Layer - Deposit 1nm of Al₂O₃ on polished side (other side from previous step)				
	IV. Photoresist(1818- for fingers patterning): - Turn on hot plate and set to 110°C* - Place n-Ge wafer on spinner (Un-polished side up) - Flood with 1818 photoresist 30 sec spin at 4,000 rpm 1min @ 110°C hot plate bake - Turn off hot plate*				
	V. Clean contact mask under solvent hood 30 sec acetone rinse 30 sec IPA rinse 30 sec DI water rinse - Dry with nitrogen on texwipe - Position mask in Aligner				
	VI. Expose 1818 - Center wafer/Align to mask - Expose using MJB3 aligner 7 sec				
	VII. Develop 1818 - Place wafer on base hood spinner 45sec develop with 351:DI (1:5) at 500rpm 30 sec DI rinse at 500rpm - Dry with nitrogen at 500rpm. - Dry on tex wipe with nitrogen - Verify develop under microscope, repeat this block if necessary				
	VIII. Deposit Contact Metals Evaporate 100Å Ti /5000Å of Al/200Å Au onto Both sides of wafer				
	IX. Lift Off / Solvent Clean 5 min acetone soak in ultrasonic bath - If necessary, Use piece of tape to lift off a some material (where no contacts are) and repeat step above. Or extend duration without using tape liftoff. 30 sec DI water rinse - Dry with nitrogen on texwipe				

Process Step #2

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Figure B-4. Page 1 of the general process used during cell fabrication of an alumina capped sample.

Wafer	Purpose	ID	Mask	Process	Print Date
n-Ge	GeTe pn-junction	9(A-C)	None	PN-Jcn Creation/Metallization	11/3/2016
	X. Anneal Junction - Bake samples in furnace at 250°C for: - A - 1hr - B - 2hr - C - 3hr				
	XI. Anneal Contacts RTA for 5 sec @ 640°C				

*-Turn off hotplate if no one else will be using it.

Figure B-5. Page 2 of the general process used during cell fabrication of an alumina capped sample.

B-2.2 Silicon Nitride.

Wafer n-Ge	Purpose GeTe pn-junction	ID 11A/B	Mask None	Process PN-Jcn Creation/Metallization	Print Date 11/9/2016
Init.	Process Step			Notes	Date Time
	I. Solvent Clean (by hand) 30 sec acetone rinse 30 sec methanol rinse 30 sec DI water rinse - Dry with nitrogen on texwipe 2 min 110°C hot plate bake*			<u>Start Date</u>	
				<u>Start Time</u>	
	II. Sputter Deposition and Verification - Place n-Ge samples <u>with witness</u> on load lock plate - Load and Sputter <i>10nm GeTe on Polished side</i> - Verify thickness of GeTe on profilometer. Record value _____				
	III. Photoresist(1818- for fingers patterning): - Turn on hot plate and set to 110°C* - Place n-Ge wafer on spinner (polished side up) - Flood with 1818 photoresist 30 sec spin at 4,000 rpm 1min @ 110°C hot plate bake - Turn off hot plate*				
	IV. Clean contact mask under solvent hood 30 sec acetone rinse 30 sec IPA rinse 30 sec DI water rinse - Dry with nitrogen on tex wipe - Position mask in Aligner				
	V. Expose 1818 - Center wafer/Align to mask - Expose using MJB3 aligner 7 sec				
	VI. Develop 1818 - Place wafer on base hood spinner 45sec develop with 351:DI (1:5) at 500rpm 30 sec DI rinse at 500rpm - Dry with nitrogen at 500rpm. - Dry on tex wipe with nitrogen - Verify develop under microscope, repeat this block if necessary				
	VII. Deposit Contact Metals Evaporate 100Å Ti /5000Å of Al/200Å Au onto Both sides of wafer				
	VIII. Lift Off / Solvent Clean 5 min acetone soak in ultrasonic bath - If necessary, extend duration 30 sec DI water rinse - Dry with nitrogen on texwipe				
	IX. Deposit Cap Layer - Using PECVD deposit 100nm of Si3N4 on the GeTe Side (Polished/Patterned side) *Incrementally deposit using temperatures : 200°C, 225°C, 250°C, 275°C, 300°C to obtain 100nm at lowest temperature possible.				

Process Step #2

Revision 0

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Figure B-6. Page 1 of the general process used during cell fabrication of an silicon nitride capped sample.

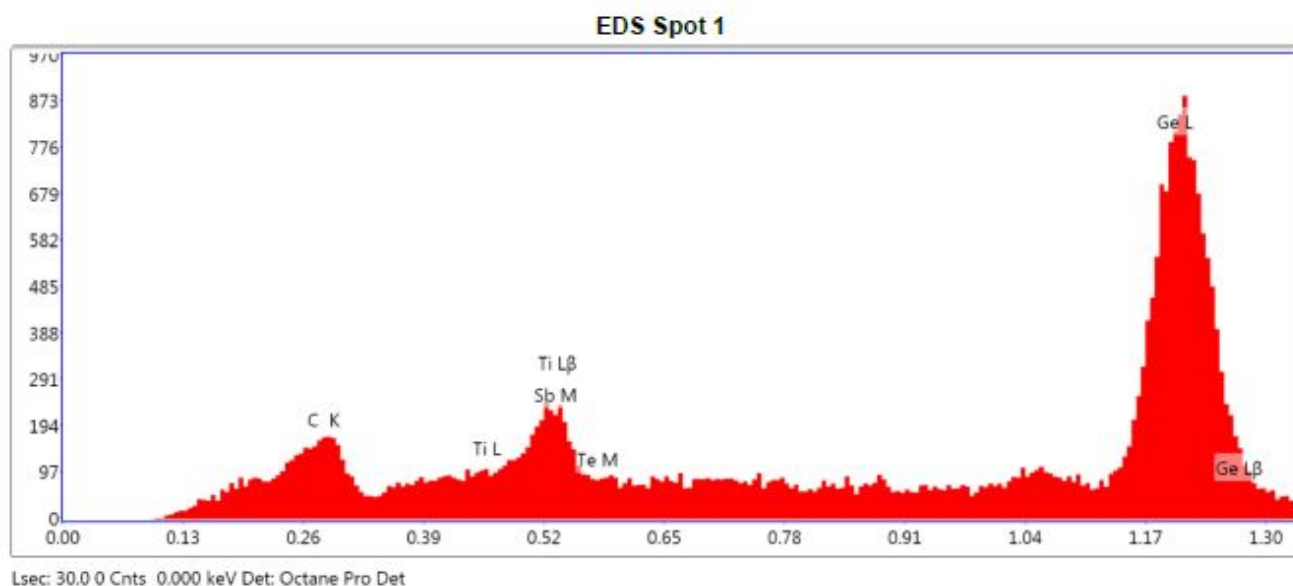
Wafer	Purpose	ID	Mask	Process	Print Date
n-Ge	GeTe pn-junction	11A/B	None	PN-jcn Creation/Metallization	11/9/2016
	X. Anneal Junction - Bake samples in furnace at 250°C for: - A - 1hr - B - 2hr *Don't start time until temp is reached				
	XI. Remove Cap Layer RIE GeTe/Patterned side to remove Si3N4 Layer				
	XII. Anneal Contacts RTA for 5 sec @ 640°C				

*-Turn off hotplate if no one else will be using it.

Figure B-7. Page 2 of the general process used during cell fabrication of an silicon nitride capped sample.

Appendix C. Scanning Electron Microscope and Energy Dispersive X-Ray Diffraction Data

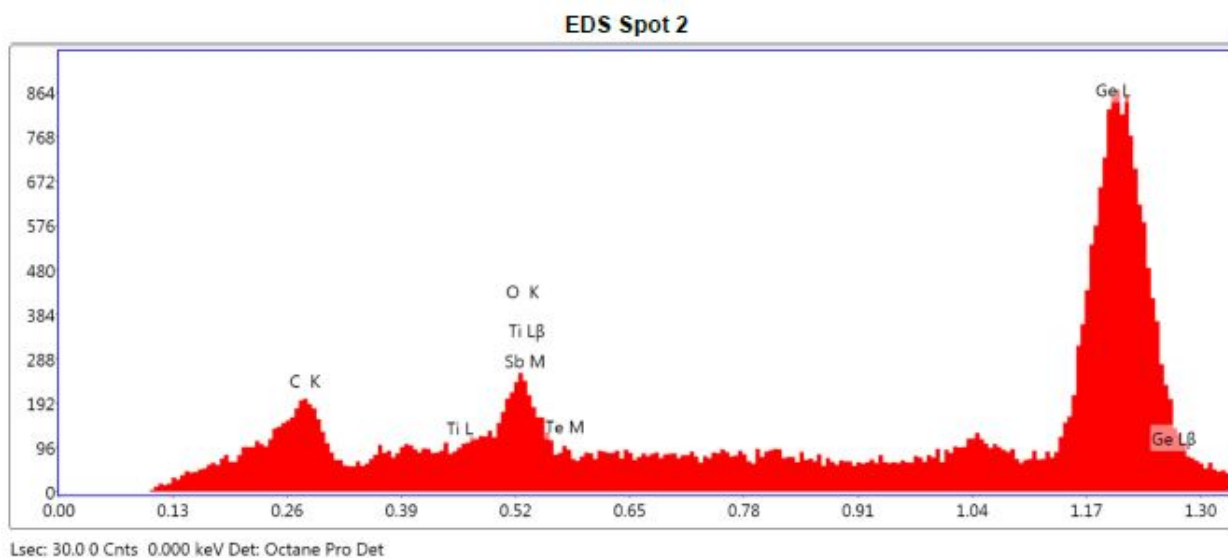
C-1 Sample 10A EDAX Analysis



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.43	18.51	83.53	14.24
SbM	13.94	7.43	47.09	41.79
TiL	2.36	3.19	5.06	53.23
TeM	2.4	1.22	6.27	47.58
GeL	77.88	69.64	233.01	23.85

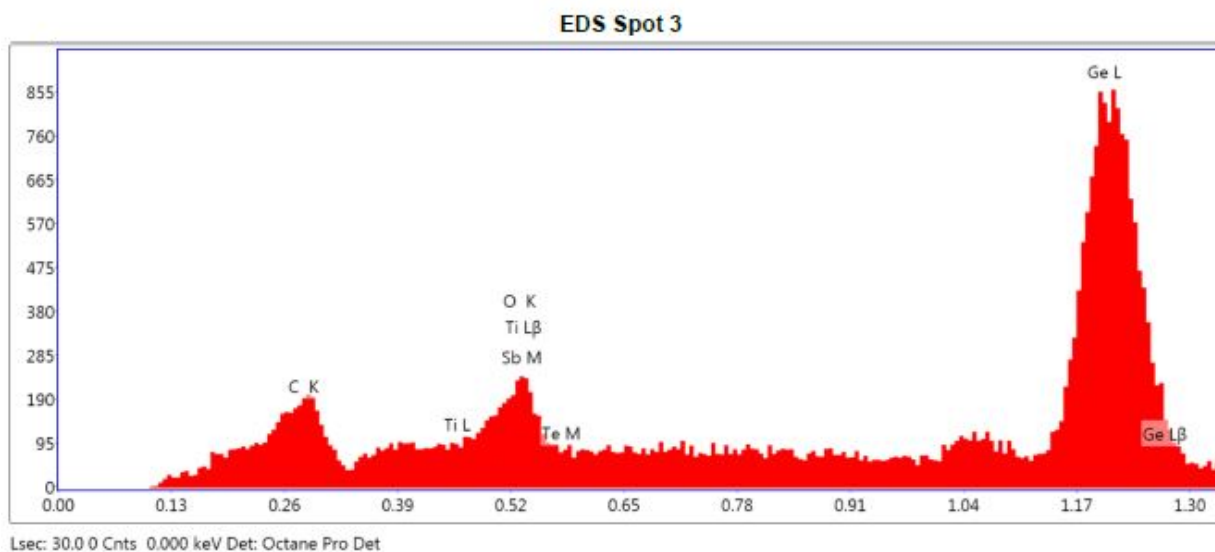
Figure C-1. Point 1 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.01	18.57	92.59	14.22
SbM	0.01	0	0.02	99.99
TiL	5.37	6.24	10.97	27.42
TeM	2.07	0.9	5.21	66.23
O K	2.37	8.24	50.97	17.39
GeL	86.17	66.04	246.59	23.47

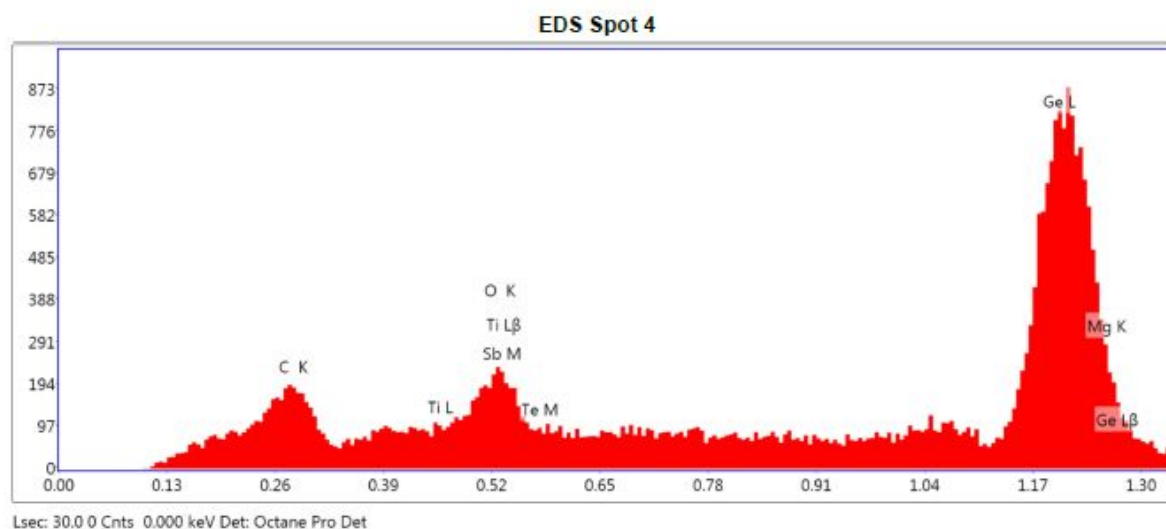
Figure C-2. Point 2 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.03	18.82	92.54	14.22
SbM	0.72	0.33	2.31	64.5
TiL	4.44	5.2	9.03	32.87
TeM	2.6	1.14	6.52	54.27
O K	2.28	7.99	48.83	17.52
GeL	85.94	66.5	244.87	23.48

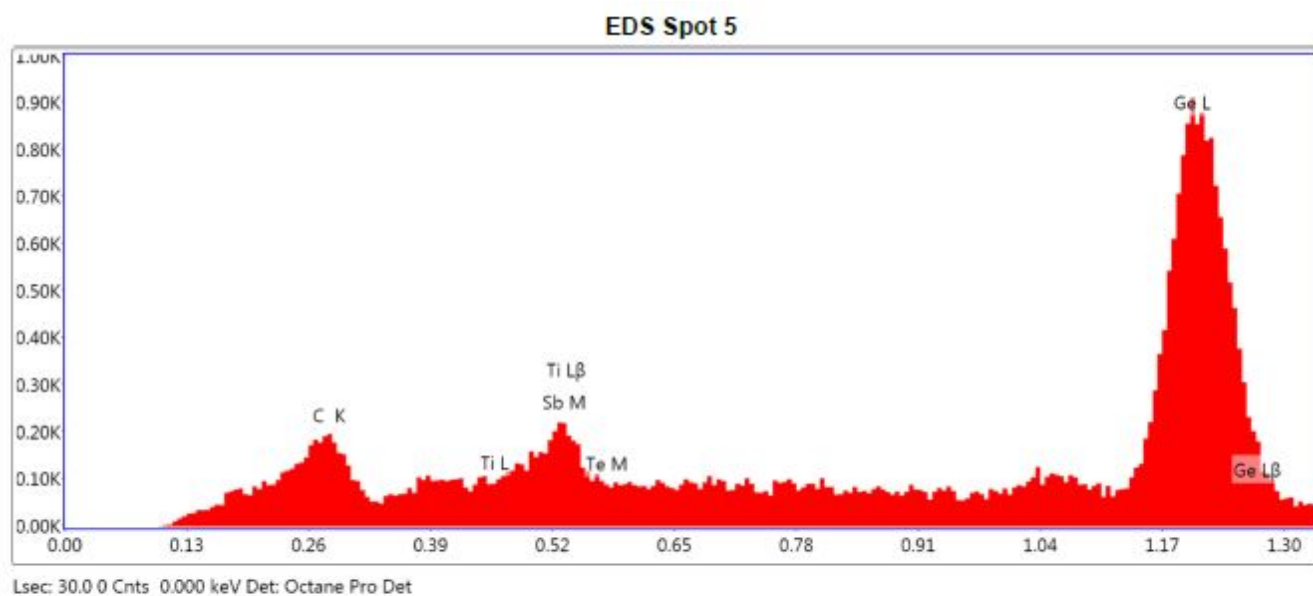
Figure C-3. Point 3 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.71	15.31	91.56	14.15
SbM	0.74	0.3	2.53	63.79
TiL	3.82	3.95	8.32	36.78
TeM	2.87	1.11	7.67	54.59
O K	2.07	6.41	47.46	17.44
GeL	76.72	52.37	232.11	23.72
MgK	10.08	20.55	53.01	30.21

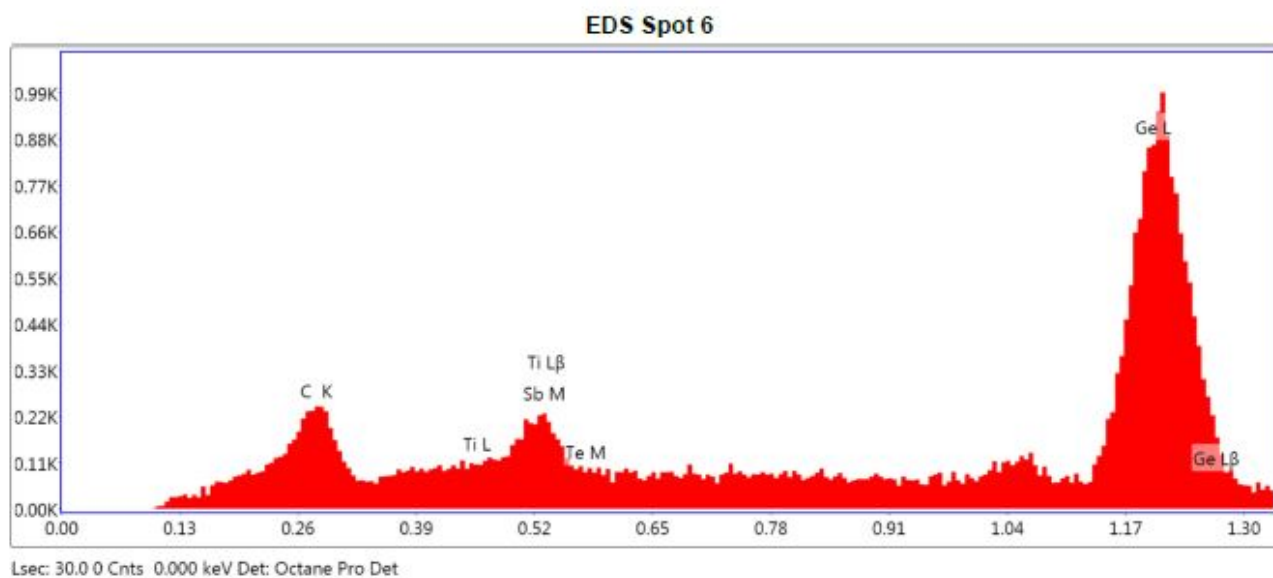
Figure C-4. Point 4 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.64	19.22	91.43	14.2
SbM	10.31	5.37	36.07	47.2
TiL	2.51	3.32	5.57	49.59
TeM	2.3	1.14	6.26	47.64
GeL	81.24	70.95	252.09	23.69

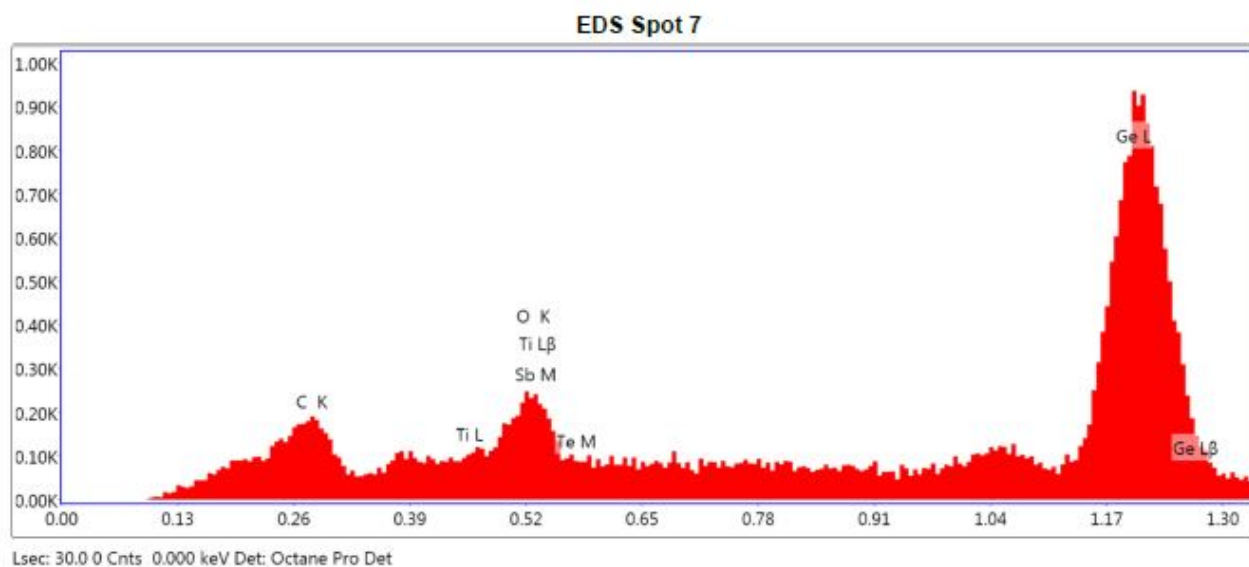
Figure C-5. Point 5 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.13	21.42	110.57	13.98
SbM	11.34	5.8	42.08	41.76
TiL	2.7	3.51	6.35	46.58
TeM	2.5	1.22	7.21	47.62
GeL	79.33	68.06	260.9	23.49

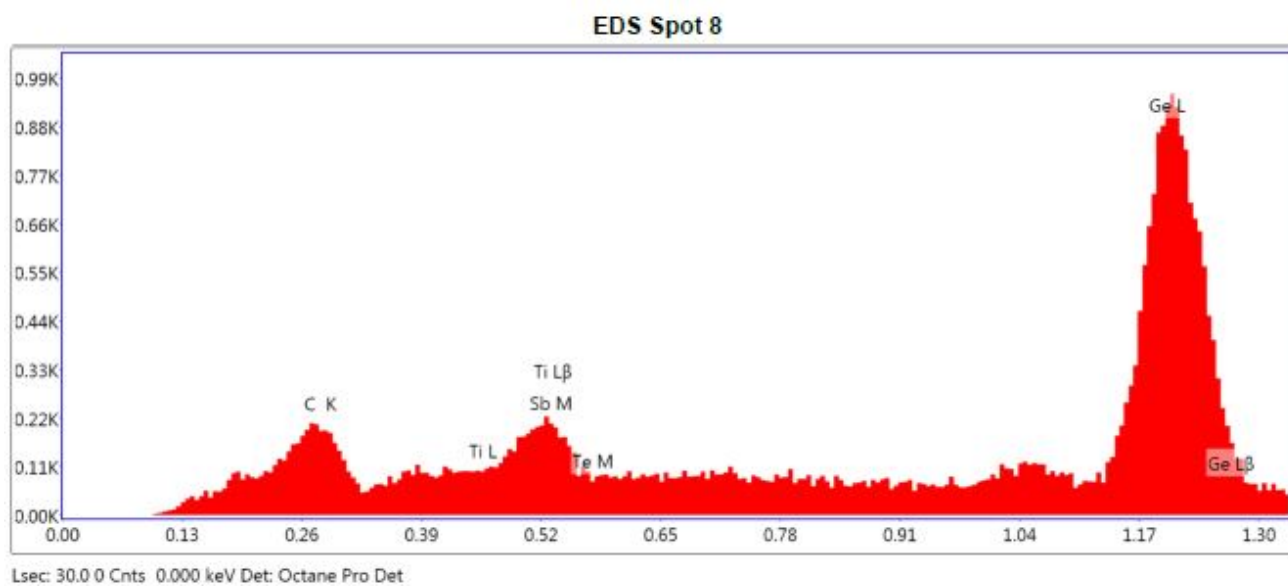
Figure C-6. Point 6 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.7	17.71	93.05	14.21
SbM	0.92	0.44	3.24	62.86
TiL	3.94	4.73	8.78	33.13
TeM	4.55	2.05	12.45	42.45
O K	2.24	8.04	52.5	17.4
GeL	84.64	67.03	263.41	23.27

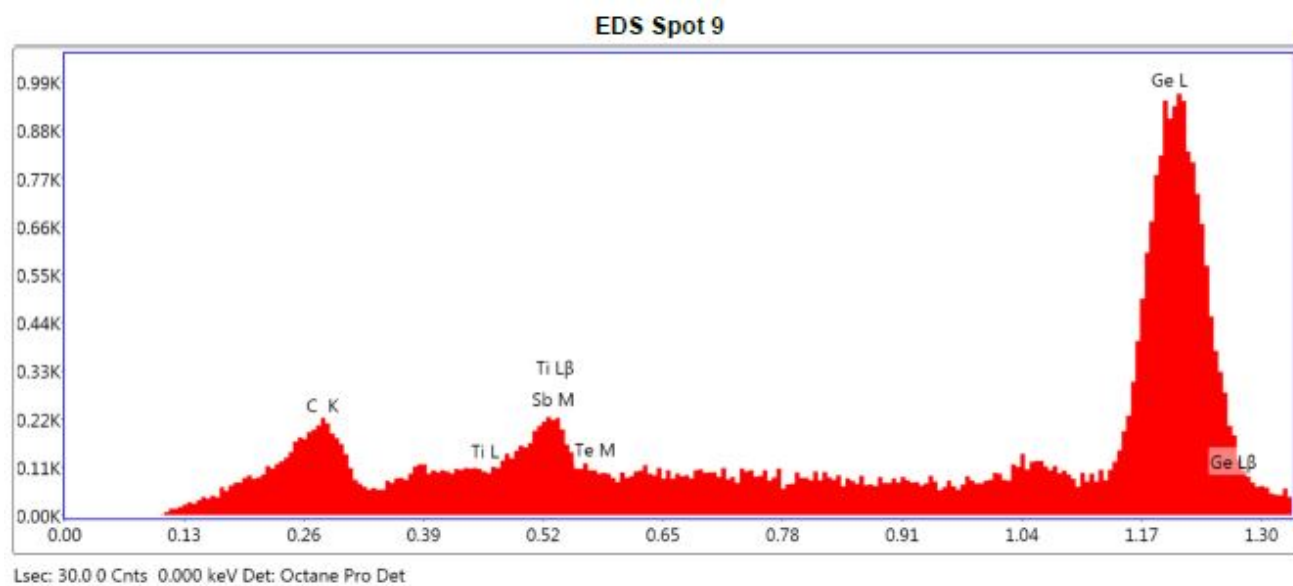
Figure C-7. Point 7 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.63	19.28	100.22	14.09
SbM	10.6	5.56	40.68	41.69
TiL	2.51	3.34	6.11	46.84
TeM	3.63	1.81	10.82	41.59
GeL	79.63	70.01	270.85	23.3

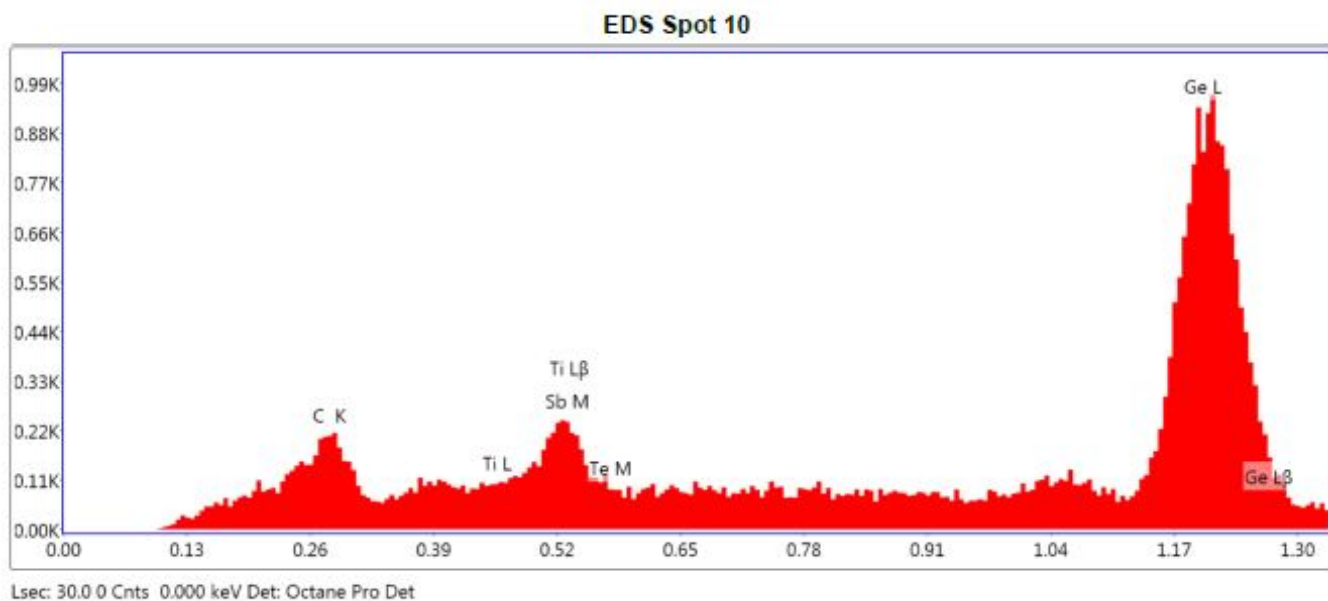
Figure C-8. Point 8 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.7	19.6	104.8	14.05
SbM	9.85	5.15	38.8	41.57
TiL	2.34	3.11	5.86	49.87
TeM	4.33	2.16	13.25	41.73
GeL	79.78	69.97	278.5	23.28

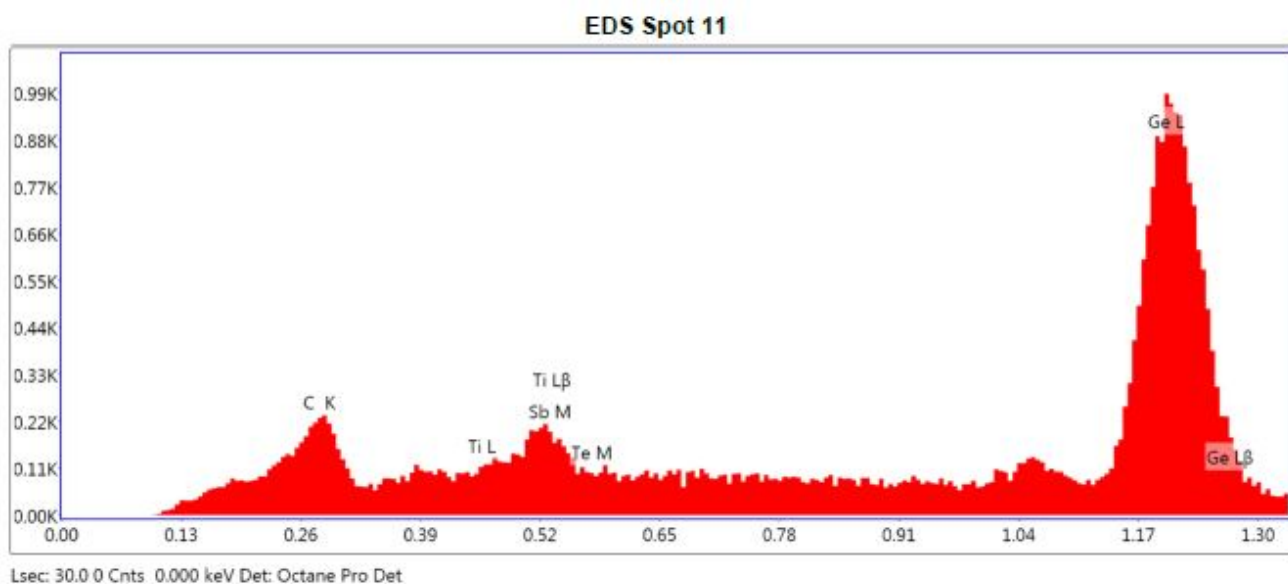
Figure C-9. Point 9 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.55	18.99	96.74	14.11
SbM	11.77	6.2	44.5	44.44
TiL	2.42	3.24	5.81	49.75
TeM	3.01	1.51	8.83	47.45
GeL	79.24	70.05	265.45	23.4

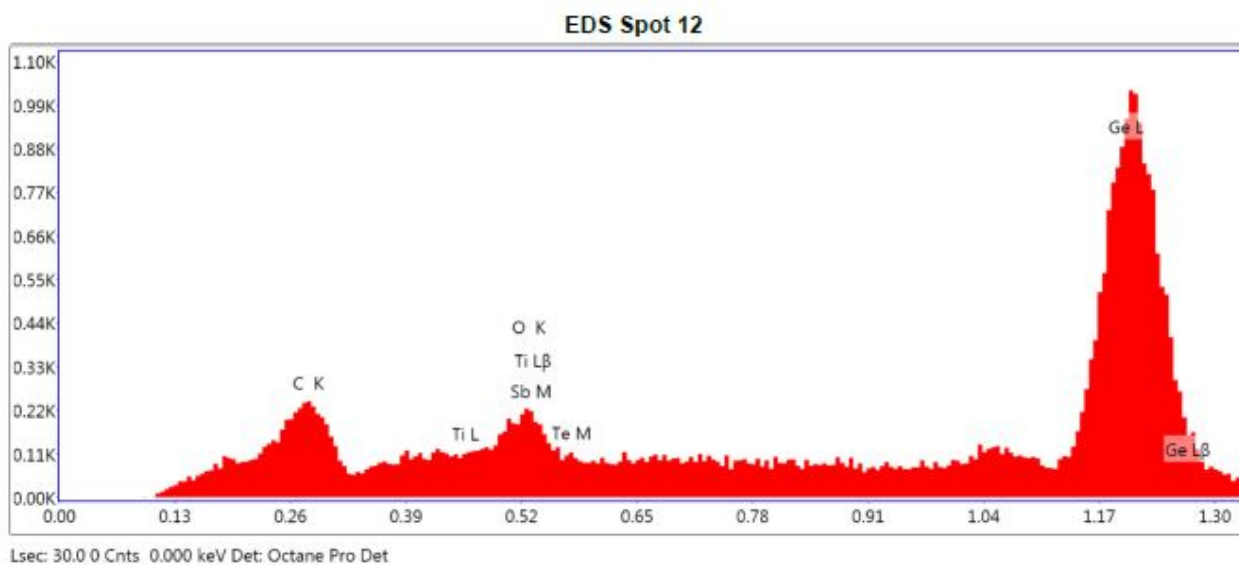
Figure C-10. Point 10 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.75	19.73	105.63	14.04
SbM	8.82	4.58	34.59	44.44
TiL	2.61	3.45	6.49	46.6
TeM	4.38	2.17	13.34	42.05
GeL	80.44	70.07	279.57	23.28

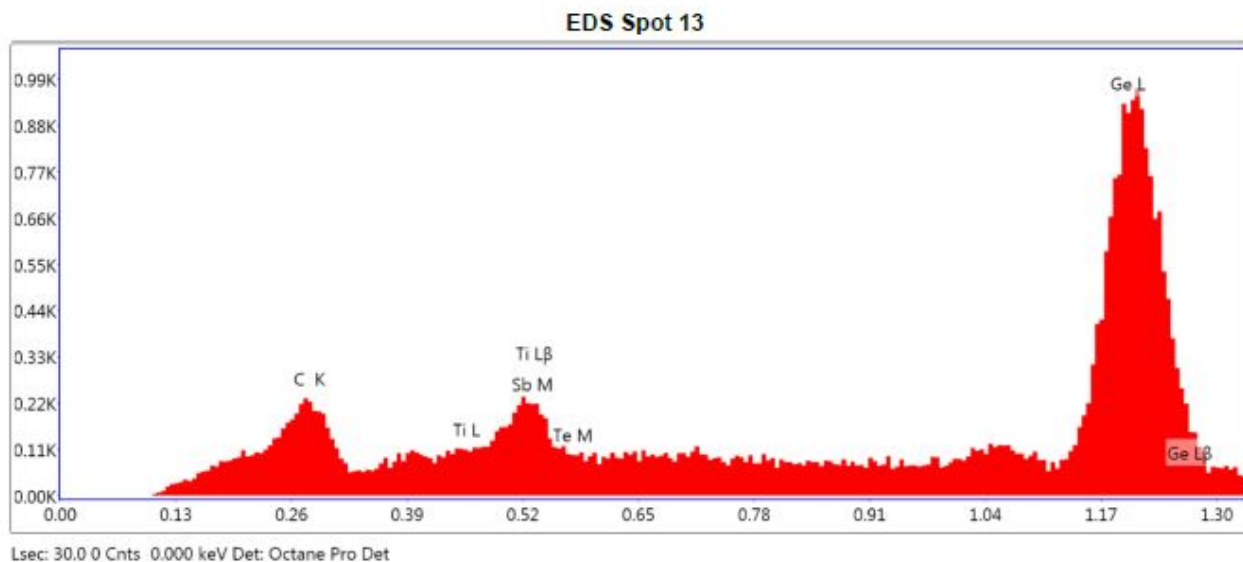
Figure C-11. Point 11 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.22	20.13	115.3	14.02
SbM	1.35	0.64	5.18	47.77
TiL	3.86	4.62	9.34	32.96
TeM	3.67	1.65	10.96	47.51
O K	1.53	5.5	39.17	17.95
GeL	85.36	67.45	289.41	23.06

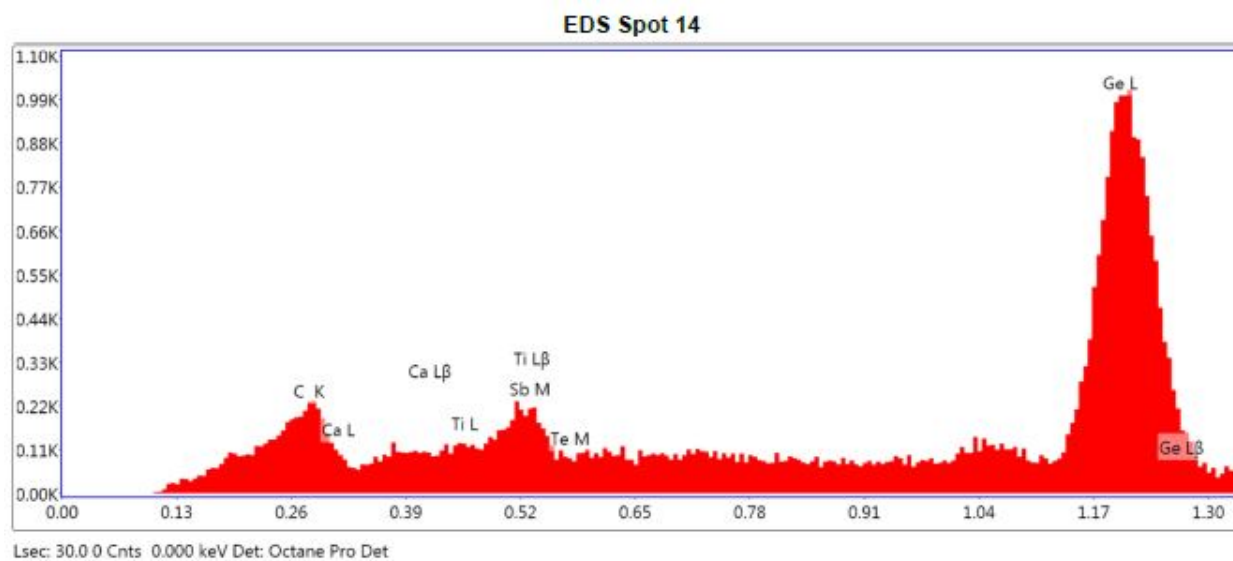
Figure C-12. Point 12 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.98	20.77	105.15	14.05
SbM	11.09	5.71	40.78	47.11
TiL	2.16	2.83	5.04	63.53
TeM	1.98	0.97	5.66	53.86
GeL	80.78	69.72	263.13	23.68

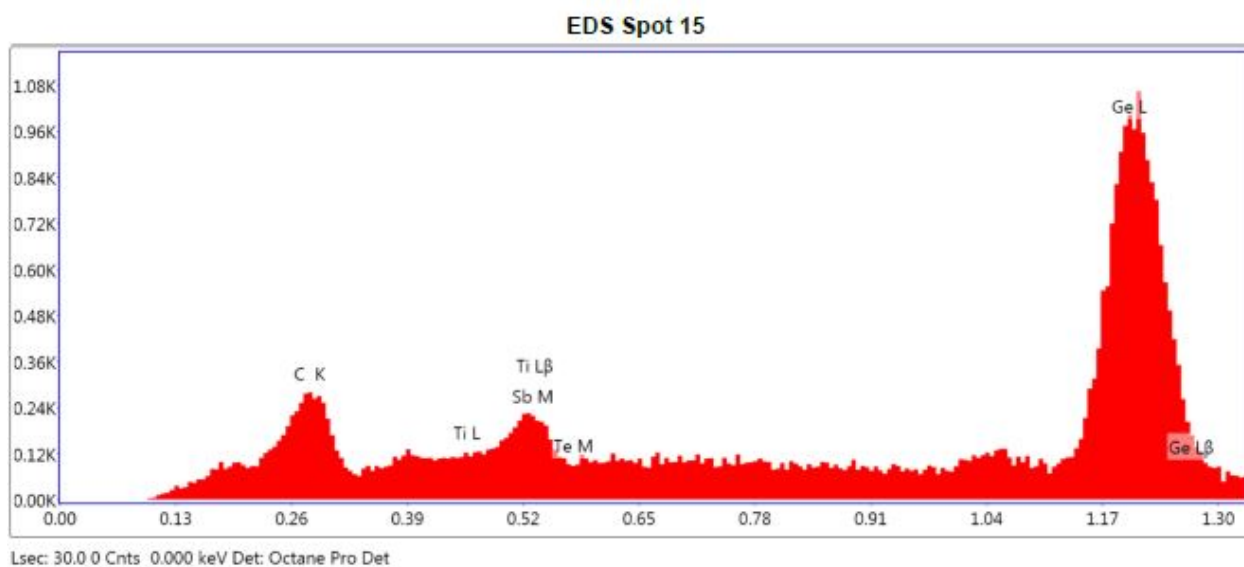
Figure C-13. Point 13 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	2.76	14.13	87.81	14.11
CaL	9.65	14.81	8.61	21.98
SbM	8.98	4.54	38.61	41.55
TiL	1.7	2.18	4.57	64.36
TeM	2.27	1.09	7.61	46.87
GeL	74.64	63.25	287.07	23.26

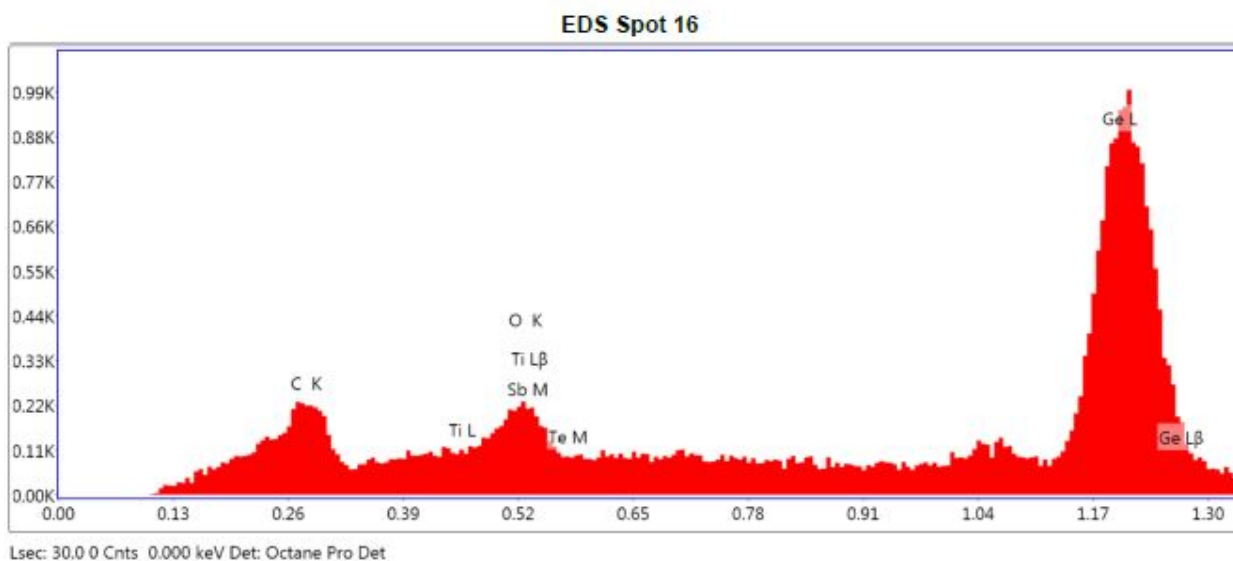
Figure C-14. Point 14 of EDAX point analysis of sample 10A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.43	22.41	123.82	13.93
SbM	9.46	4.72	36.84	50.19
TiL	2.71	3.43	6.68	48.96
TeM	0.92	0.44	2.8	67.87
GeL	82.47	68.99	284.74	23.53

Figure C-15. Point 15 of EDAX point analysis of sample 10A with element composition analysis.

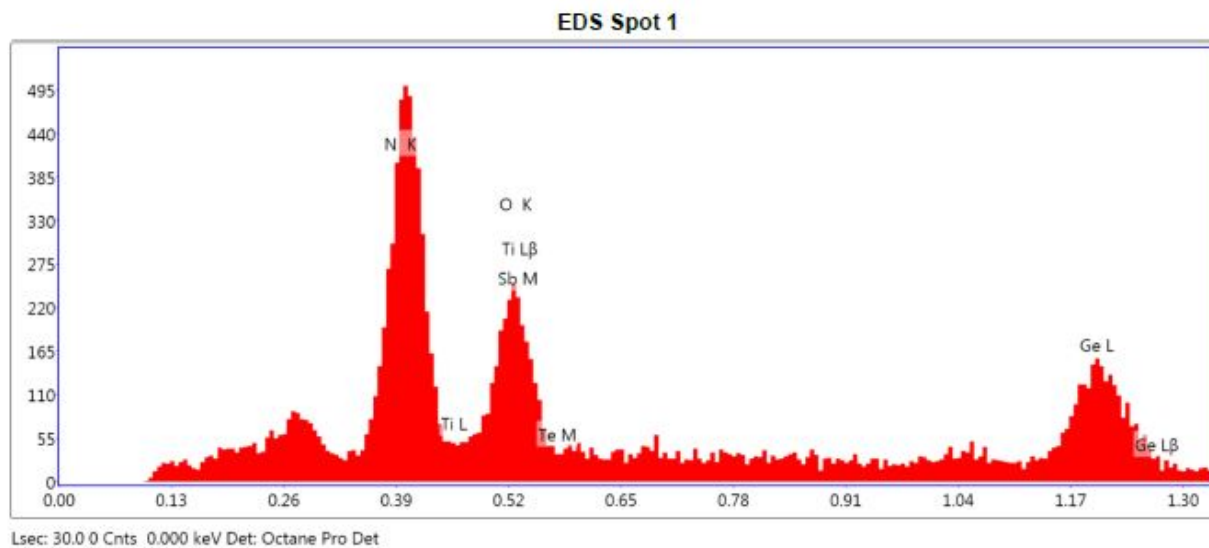


eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.19	19.87	112.12	14.03
SbM	1	0.47	3.72	61.93
TiL	4.07	4.84	9.63	30.96
TeM	3.85	1.72	11.2	47.52
O K	1.81	6.44	45.13	17.63
GeL	85.08	66.68	281.58	23.23

Figure C-16. Point 16 of EDAX point analysis of sample 10A with element composition analysis.

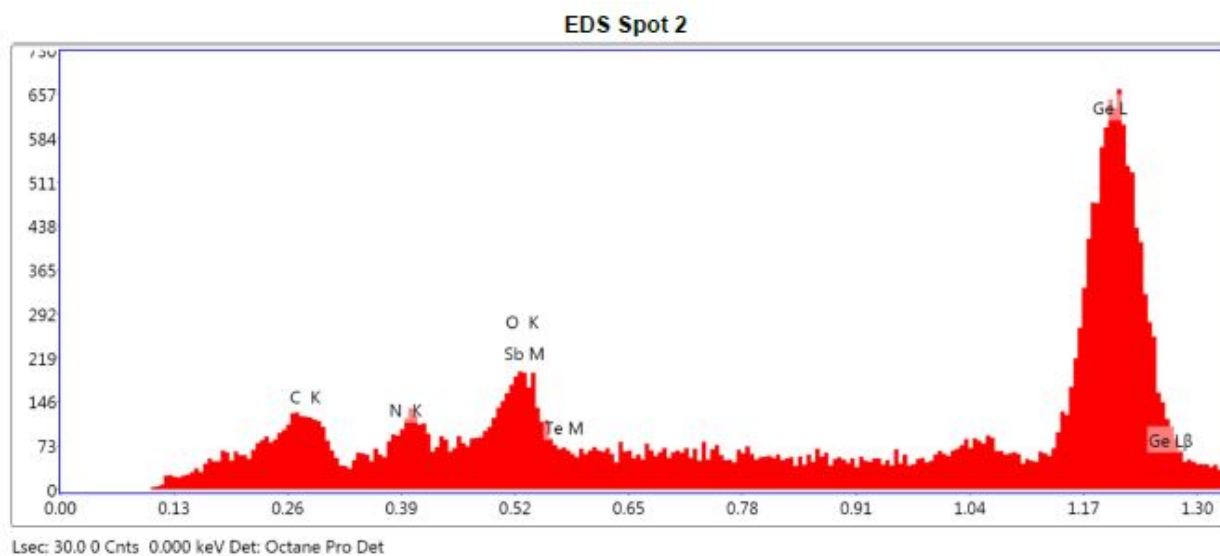
C-2 Sample 11A EDAX Analysis



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
N K	23.03	57.53	130.73	13.19
SbM	14.81	4.26	17.34	18.26
TiL	0.01	0.01	0.01	99.99
TeM	12.55	3.44	11.2	30.87
O K	6.38	13.94	50.24	16.4
GeL	43.22	20.83	44.17	27.76

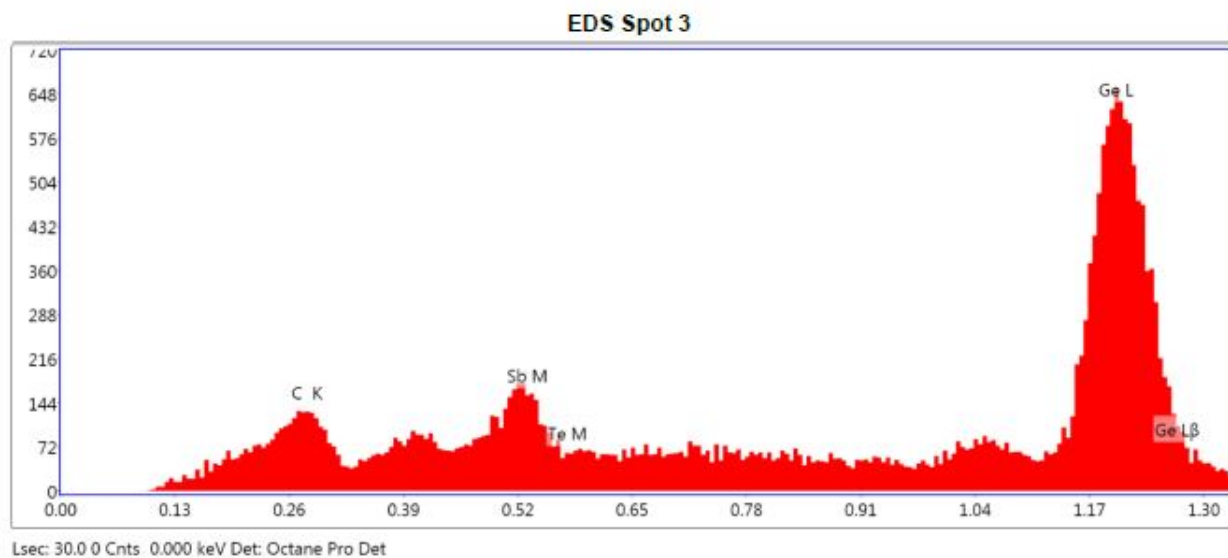
Figure C-17. Point 1 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.58	15.78	62.55	14.62
N K	2.89	10.95	31.6	17.12
SbM	1.81	0.79	4.44	45.17
TeM	3.48	1.45	6.64	42.09
O K	2.57	8.51	42.04	17.62
GeL	85.66	62.53	184.86	23.91

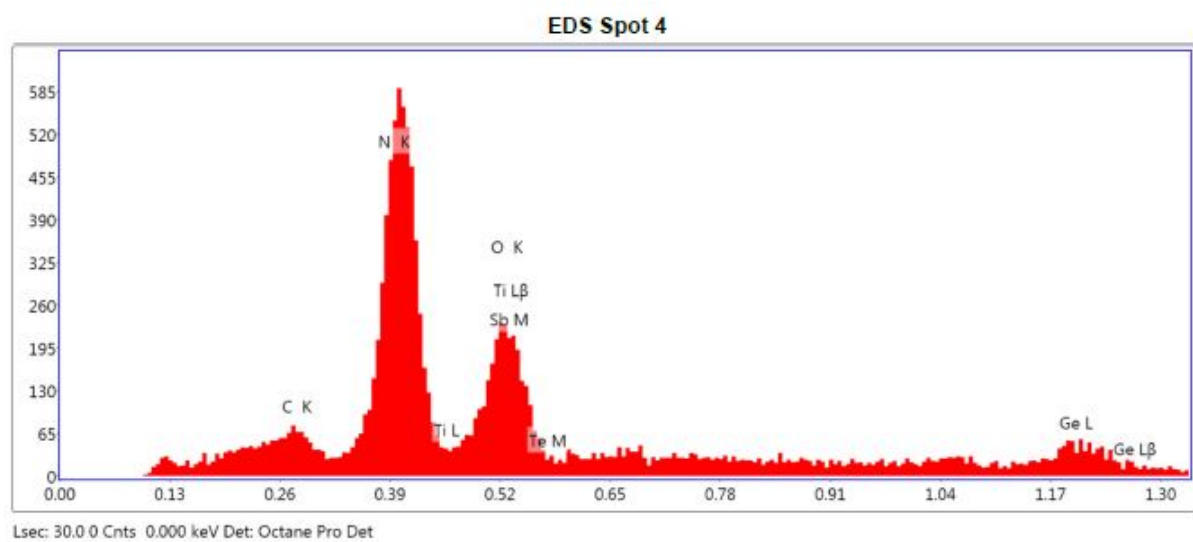
Figure C-18. Point 2 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.48	18.93	63.94	14.58
SbM	14.98	8.03	38.47	24.21
TeM	0.74	0.38	1.47	54.08
GeL	80.8	72.66	183.49	24.3

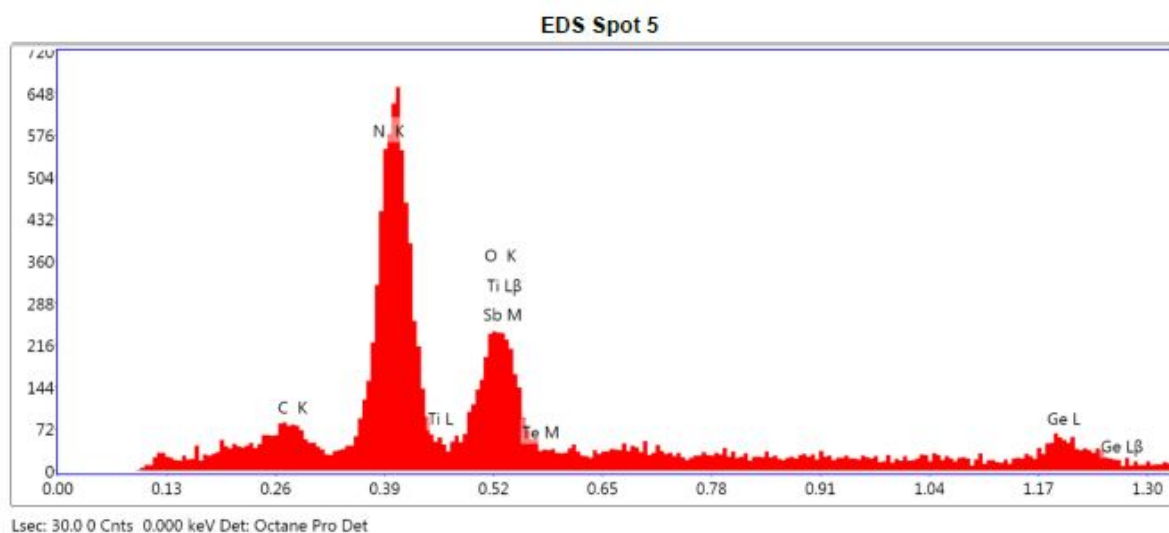
Figure C-19. Point 3 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.97	9.76	34.25	14.02
N K	38.24	64.38	149.67	12.78
SbM	22.27	4.31	17.3	19.02
TiL	0.02	0.01	0.01	99.99
TeM	9.31	1.72	5.5	43.15
O K	10.12	14.92	52.96	16.28
GeL	15.06	4.89	10.14	36.5

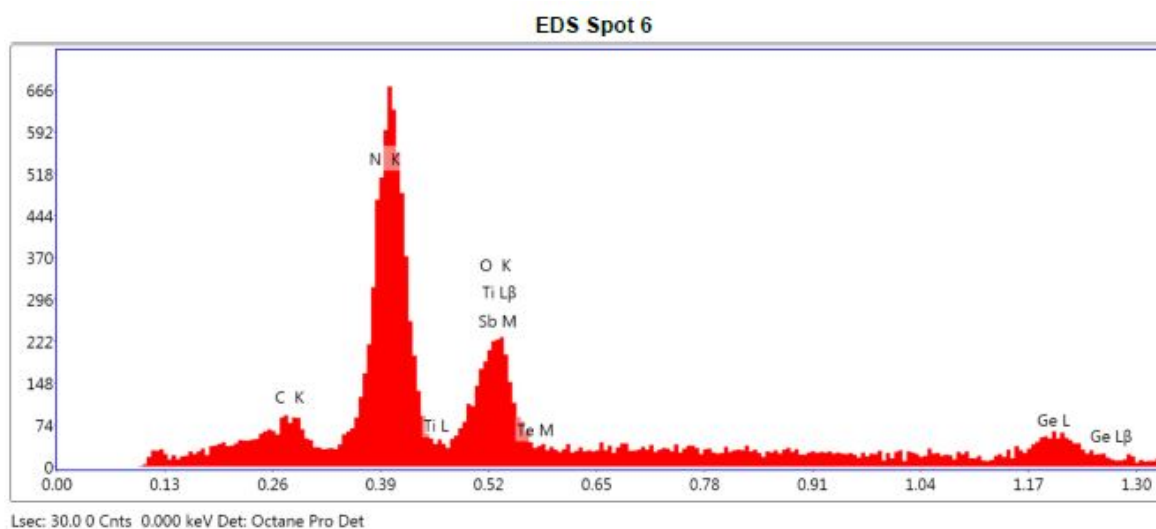
Figure C-20. Point 4 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.23	9.51	37.01	13.75
N K	32.27	62.28	161.54	12.6
SbM	22.32	4.96	22.37	16.34
TiL	0.02	0.01	0.01	99.99
TeM	15.58	3.3	11.83	28.73
O K	7.9	13.35	53.42	16.34
GeL	17.69	6.59	15.38	31.75

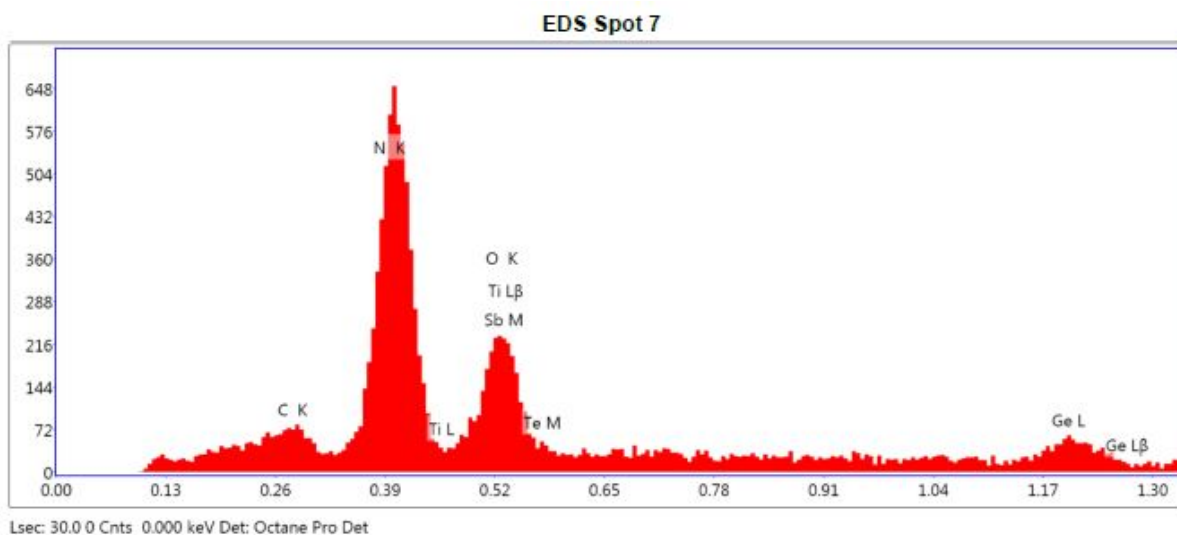
Figure C-21. Point 5 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	5.06	10.4	40.21	13.58
N K	36.81	64.85	166.46	12.64
SbM	21.34	4.33	19.23	17.44
TiL	0.02	0.01	0.01	99.99
TeM	11.52	2.23	7.91	39.38
O K	7.99	12.32	48.46	16.5
GeL	17.26	5.87	13.51	33.63

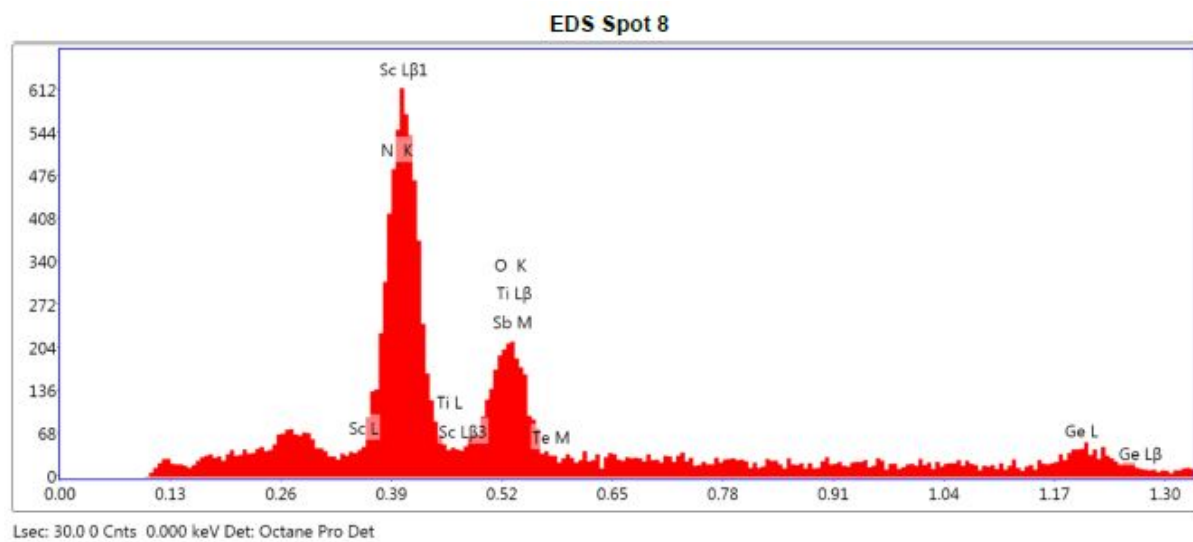
Figure C-22. Point 6 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.76	9.91	38.08	13.66
N K	36.26	64.8	165.32	12.64
SbM	22.16	4.56	20.11	17.37
TiL	0.02	0.01	0.01	99.99
TeM	12.15	2.38	8.39	39.63
O K	8.06	12.61	49.3	16.47
GeL	16.59	5.72	13.08	33.74

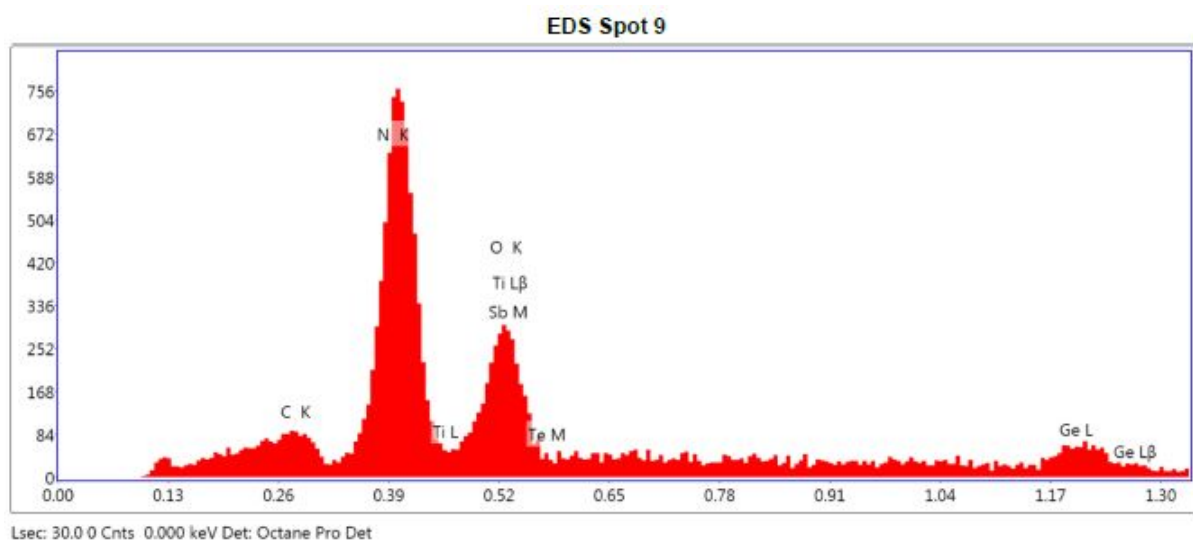
Figure C-23. Point 7 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
ScL	9.19	6.76	6.16	14.18
N K	25.52	60.26	123.86	12.84
SbM	22.24	6.04	21.29	15.86
TiL	0.02	0.01	0.01	99.99
TeM	17.88	4.63	12.97	26.66
O K	6.73	13.9	43.4	16.83
GeL	18.42	8.39	15.5	30.6

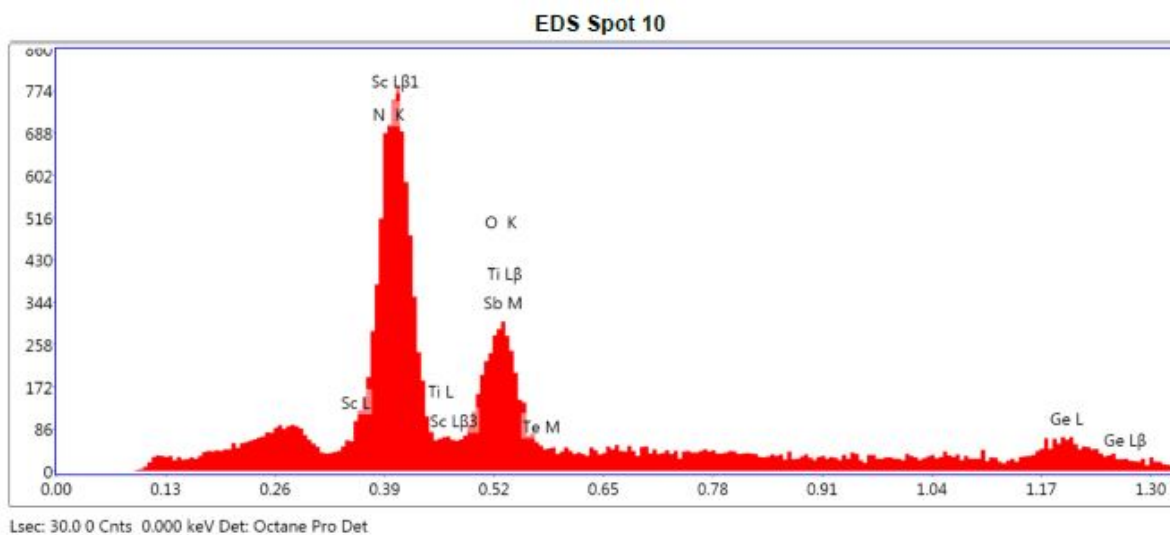
Figure C-24. Point 8 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	5.22	9.8	44.48	13.34
N K	41.09	66.12	198.48	12.45
SbM	21.68	4.01	20.7	18.78
TiL	0.02	0.01	0.01	99.99
TeM	7.92	1.4	5.76	42.65
O K	10.18	14.34	65.4	16.02
GeL	13.89	4.31	11.51	36.21

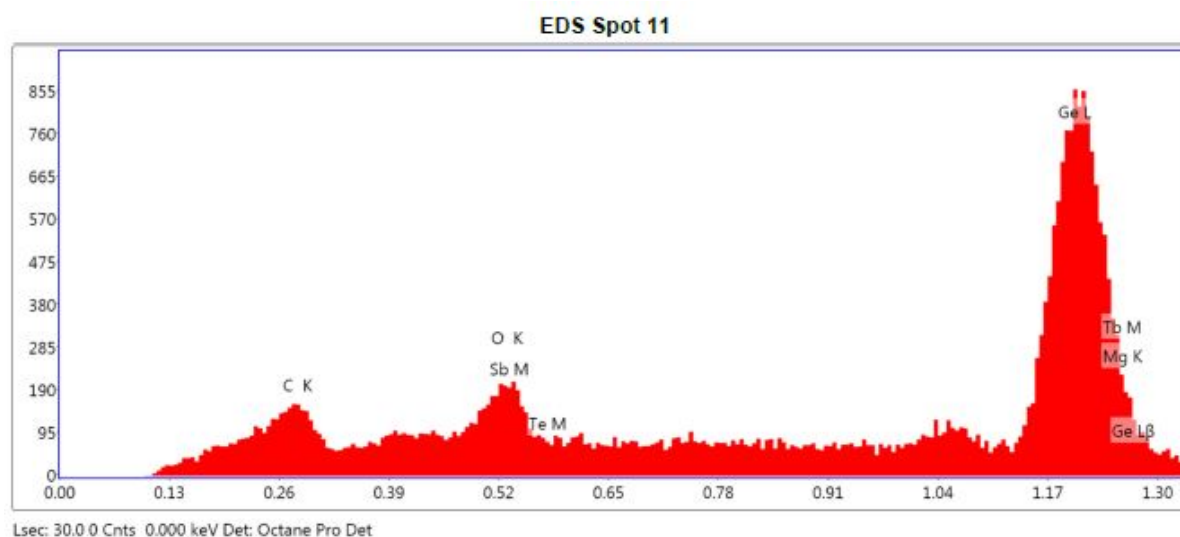
Figure C-25. Point 9 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
ScL	9.79	6.69	7.72	14.74
N K	27.95	61.32	159.89	12.78
SbM	23.34	5.89	26.2	16.27
TiL	0.02	0.01	0.01	99.99
TeM	13.62	3.28	11.61	33.08
O K	8.09	15.54	61.13	16.27
GeL	17.2	7.28	16.96	31.59

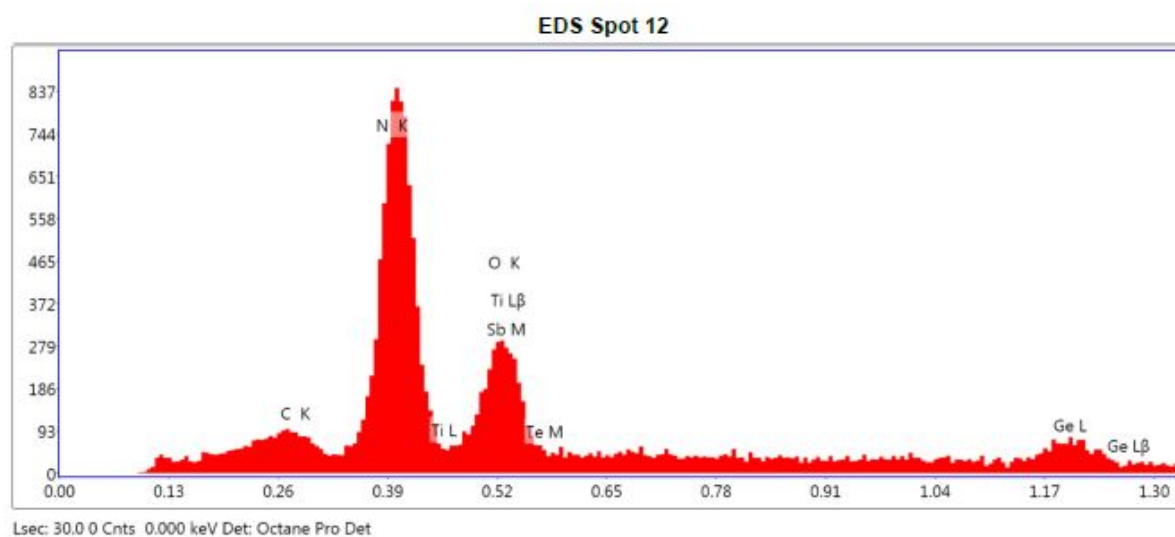
Figure C-26. Point 10 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.05	16.86	81.34	14.31
SbM	5.27	2.87	19.61	21.27
TeM	4.13	2.15	11.95	36.68
O K	1.28	5.32	31.97	20.91
GeL	74.23	67.78	245.37	23.24
MgK	0.01	0.02	0.03	99.99
TbM	12.02	5.01	14.4	33.02

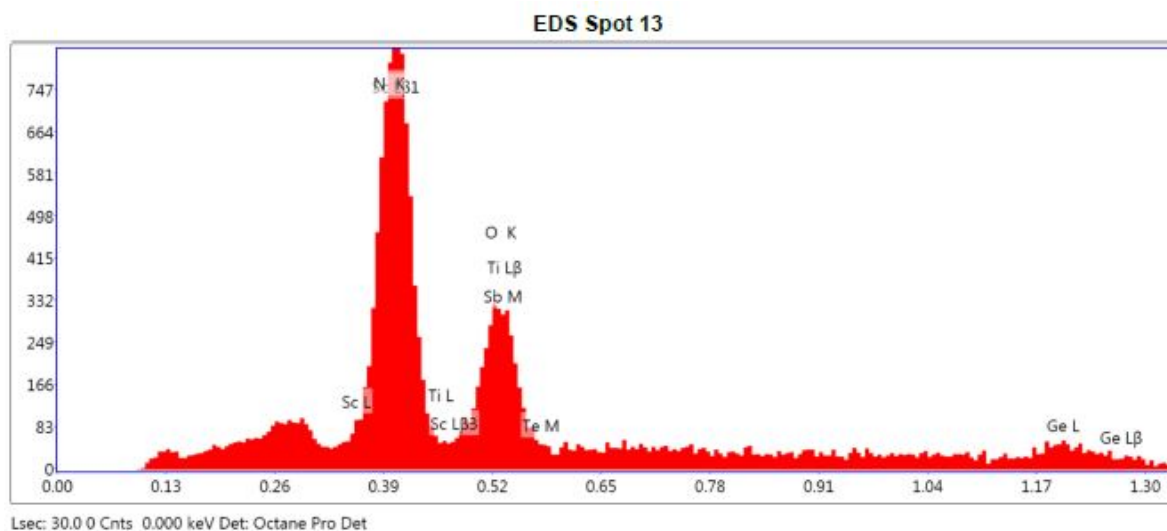
Figure C-27. Point 11 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	4.64	9.77	49.94	13.32
N K	36.25	65.37	222.48	12.36
SbM	21.23	4.4	25.98	16.42
TiL	0.01	0.01	0.01	99.99
TeM	12.19	2.41	11.37	31.64
O K	7.4	11.68	60.98	16.13
GeL	18.27	6.36	19.44	31.28

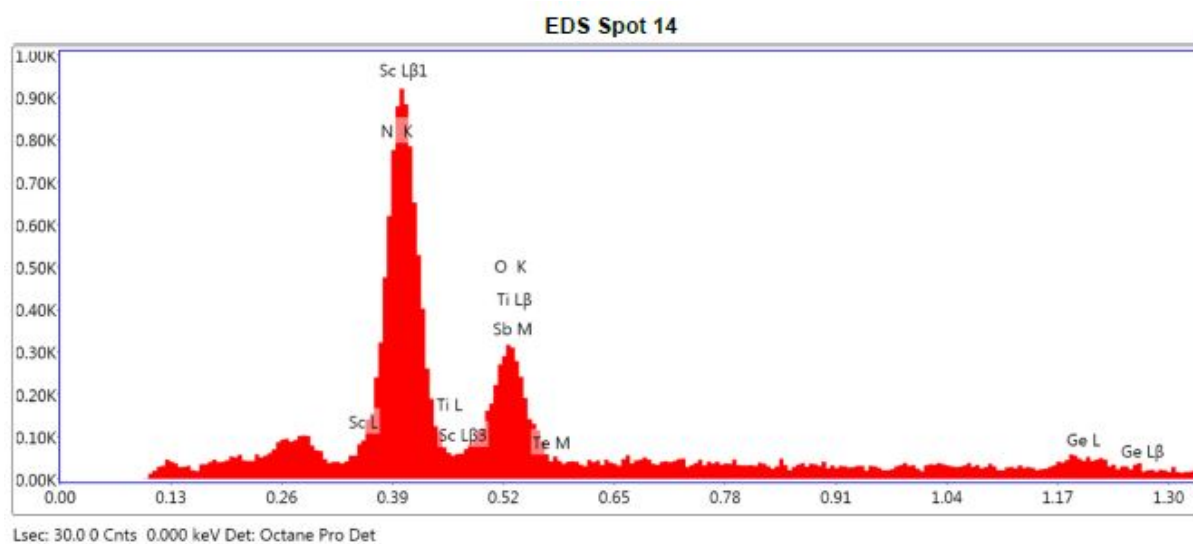
Figure C-28. Point 12 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
ScL	10.14	6.52	8.33	14.29
N K	30.93	63.82	184.13	12.48
SbM	23.64	5.61	27.37	16.24
TiL	0.01	0.01	0.01	99.99
TeM	13.9	3.15	12.21	33.24
O K	8.79	15.88	68.52	16.12
GeL	12.59	5.01	12.8	33.8

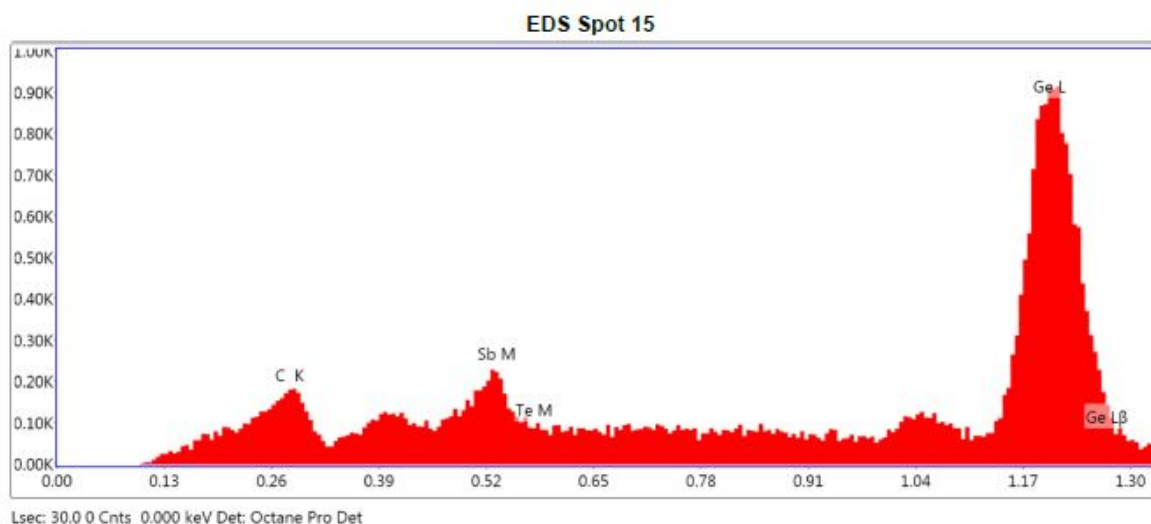
Figure C-29. Point 13 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
ScL	10.17	6.32	8.19	14.78
N K	33.14	66.14	193.49	12.43
SbM	23.85	5.48	27	16.52
TiL	0.02	0.01	0.01	99.99
TeM	12.38	2.71	10.66	35.87
O K	8.42	14.71	64.13	16.22
GeL	12.02	4.63	11.96	36.07

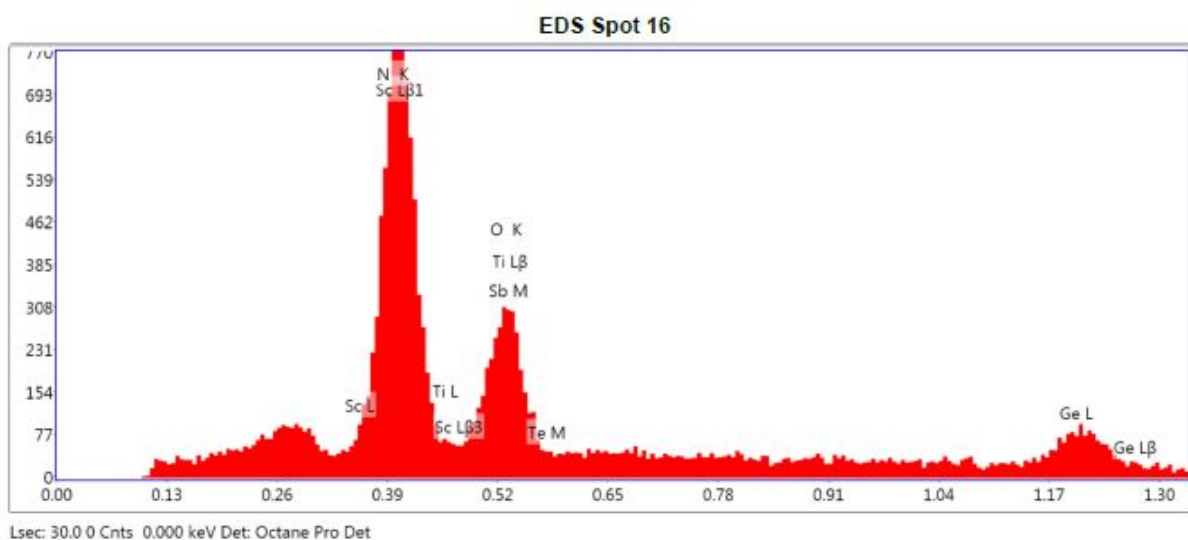
Figure C-30. Point 14 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
C K	3.29	17.97	85.06	14.3
SbM	13.12	7.07	47.63	23.06
TeM	1.4	0.72	3.95	46.98
GeL	82.19	74.25	263.77	23.58

Figure C-31. Point 15 of EDAX point analysis of sample 11A with element composition analysis.



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %
ScL	10.08	6.52	8.05	15.19
N K	30.15	62.57	174.67	12.7
SbM	21.48	5.13	24.38	17.24
TiL	0.02	0.01	0.01	99.99
TeM	10.86	2.47	9.39	42.89
O K	8.69	15.79	66.31	16.14
GeL	18.73	7.5	18.69	32.24

Figure C-32. Point 16 of EDAX point analysis of sample 11A with element composition analysis.

Appendix D. Calculated Barrier Junction Data Plots

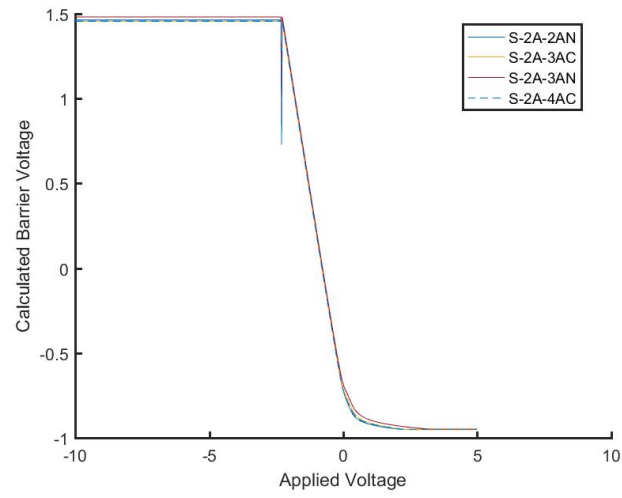


Figure D-1. Calculated depleted region voltage for sample set 2 using the ideal diode equation for a hetero pn-junction.

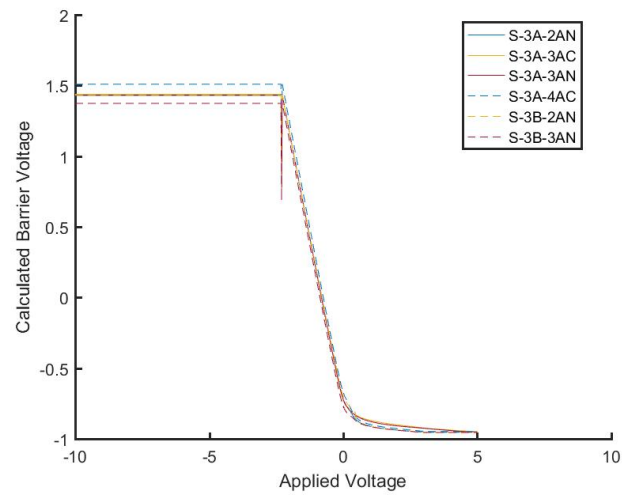


Figure D-2. Calculated depleted region voltage for sample set 3 using the ideal diode equation for a hetero pn-junction.

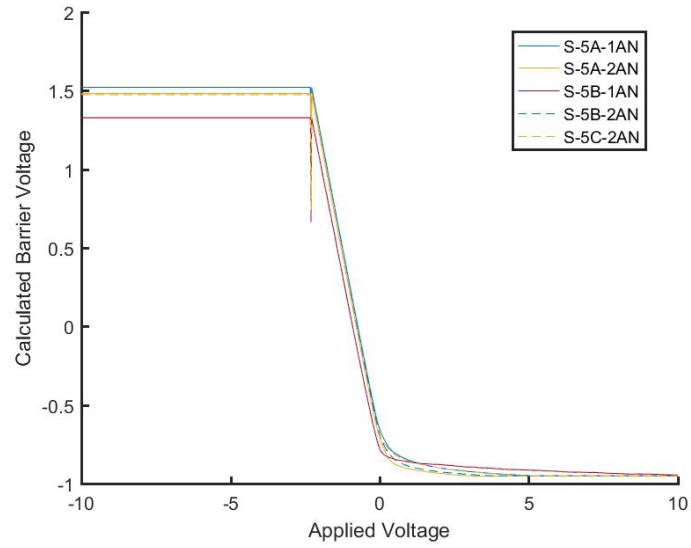


Figure D-3. Calculated depleted region voltage for sample set 5 using the ideal diode equation for a hetero pn-junction.

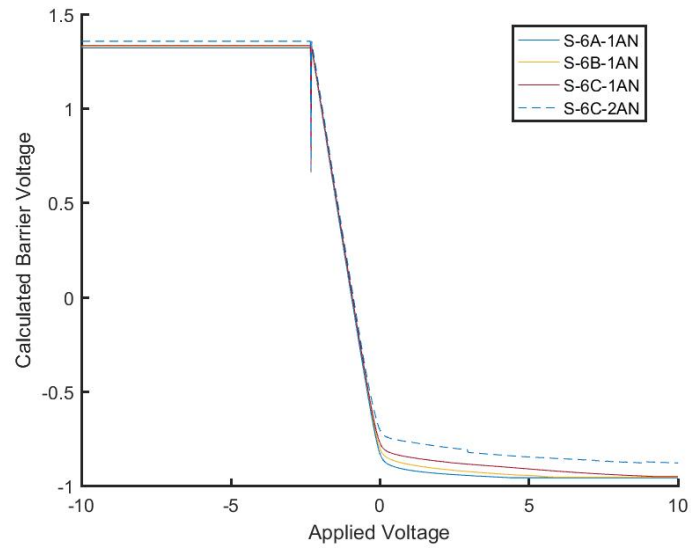


Figure D-4. Calculated depleted region voltage for sample set 6 using the ideal diode equation for a hetero pn-junction.

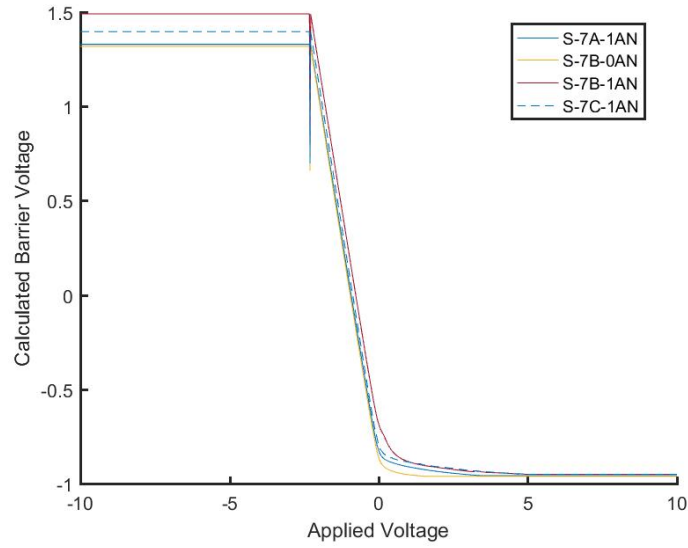


Figure D-5. Calculated depleted region voltage for sample set 7 using the ideal diode equation for a hetero pn-junction.

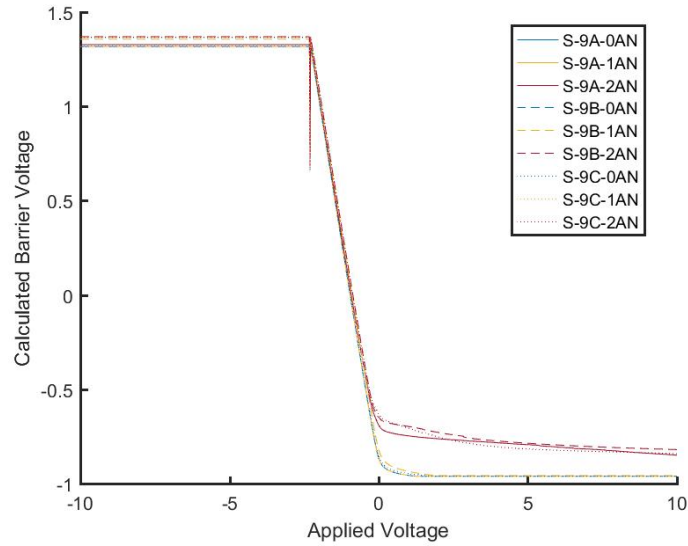


Figure D-6. Calculated depleted region voltage for sample set 9 using the ideal diode equation for a hetero pn-junction.

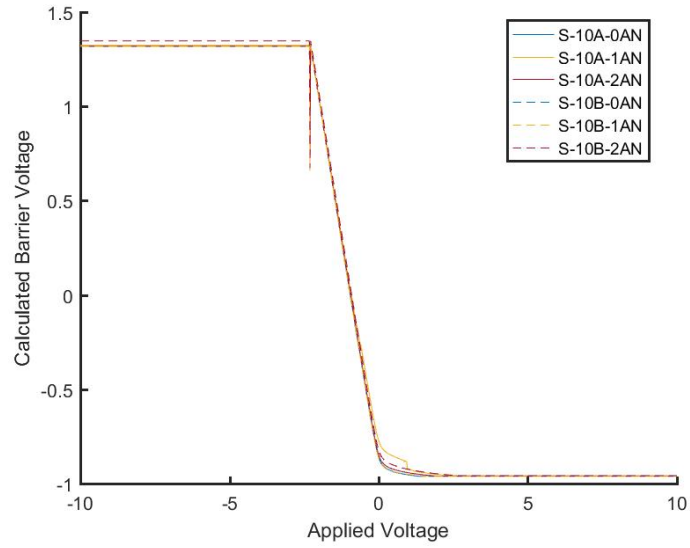


Figure D-7. Calculated depleted region voltage for sample set 10 using the ideal diode equation for a hetero pn-junction.

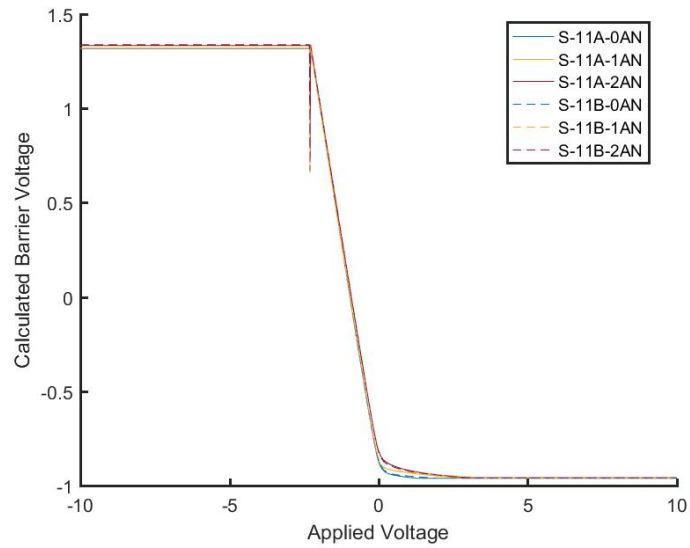


Figure D-8. Calculated depleted region voltage for sample set 11 using the ideal diode equation for a hetero pn-junction.

Appendix E. Reflectance and Transmittance Data Plots

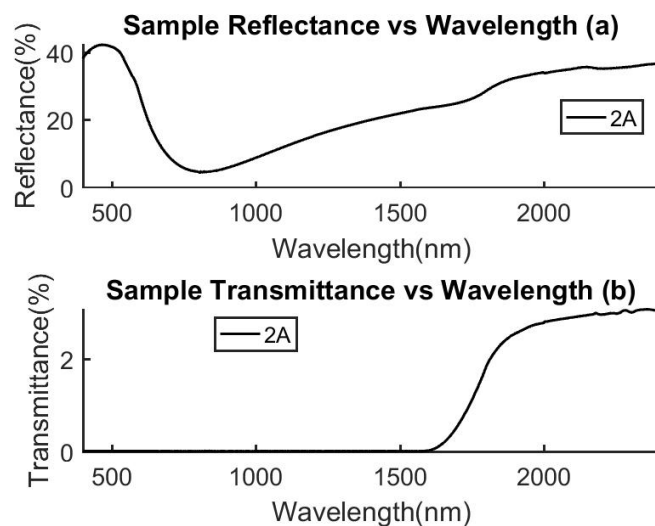


Figure E-1. Reflectance(a) and Transmittance(b) plots for Sample Set 2.

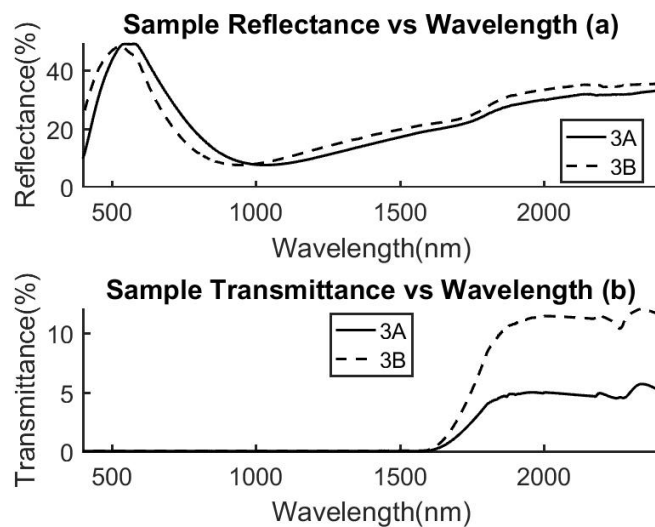


Figure E-2. Reflectance(a) and Transmittance(b) plots for Sample Set 3.

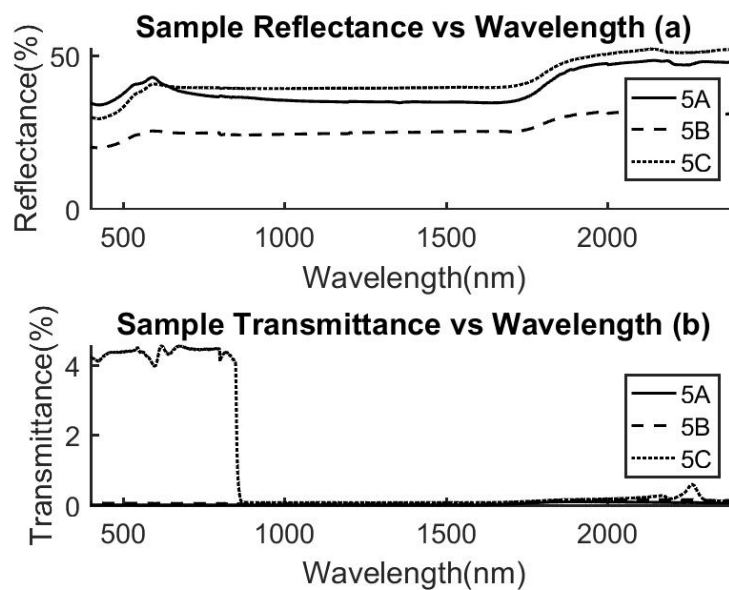


Figure E-3. Reflectance(a) and Transmittance(b) plots for Sample Set 5.

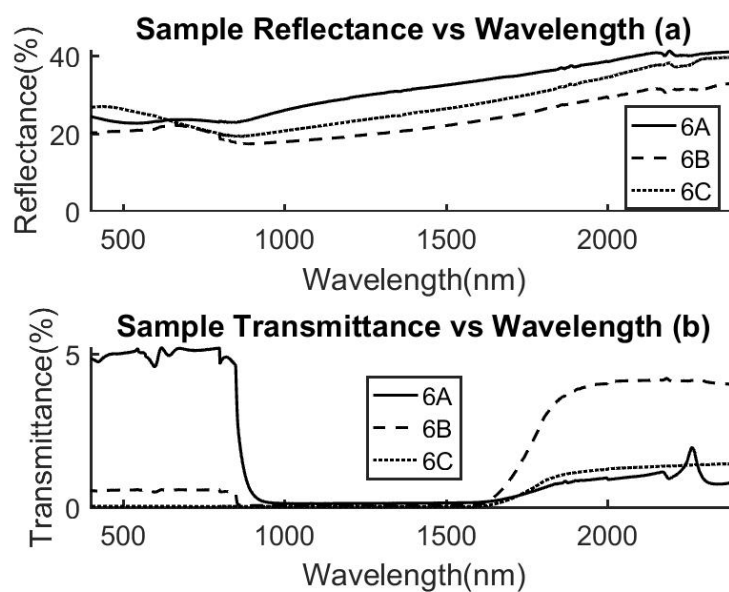


Figure E-4. Reflectance(a) and Transmittance(b) plots for Sample Set 6.

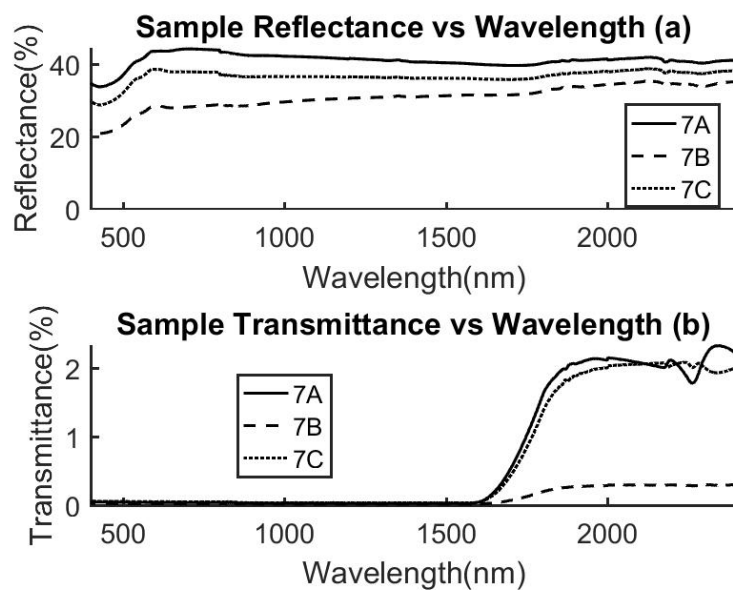


Figure E-5. Reflectance(a) and Transmittance(b) plots for Sample Set 7.

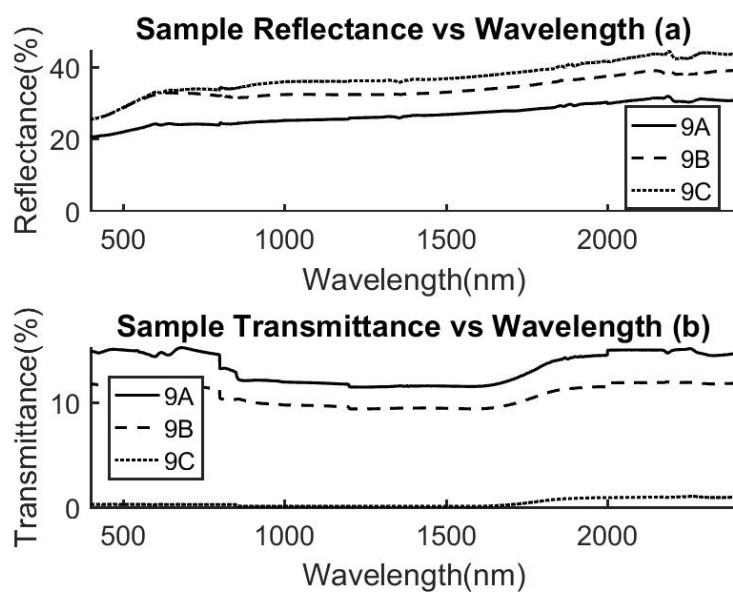


Figure E-6. Reflectance(a) and Transmittance(b) plots for Sample Set 9.

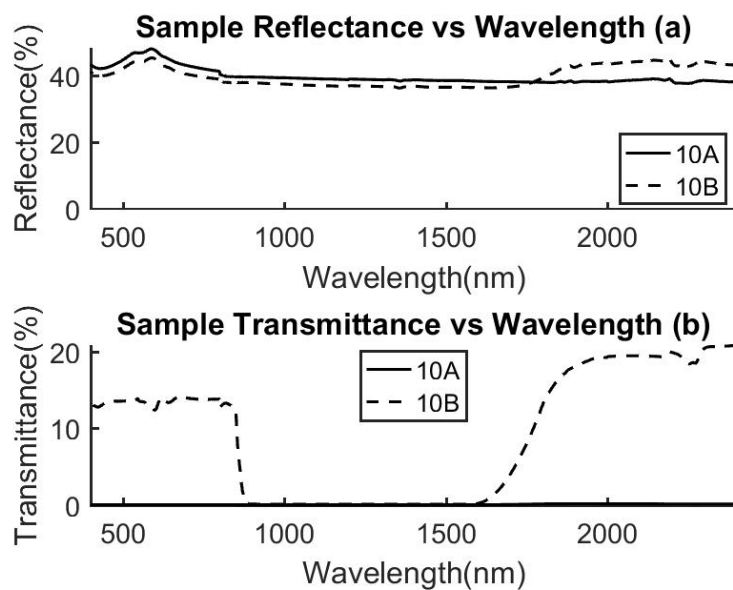


Figure E-7. Reflectance(a) and Transmittance(b) plots for Sample Set 10.

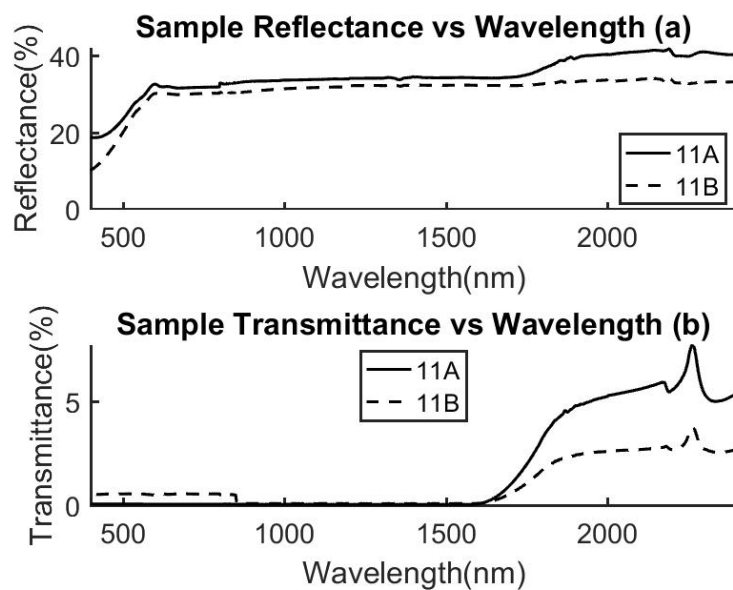


Figure E-8. Reflectance(a) and Transmittance(b) plots for Sample Set 11.

Appendix F. Diode Test Data Plots

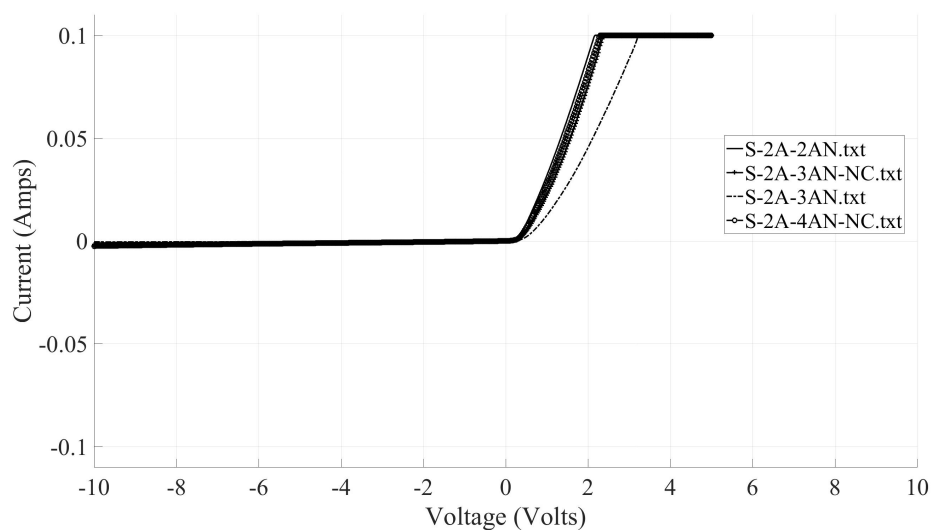


Figure F-1. Diode Test plot for Sample Set 2.

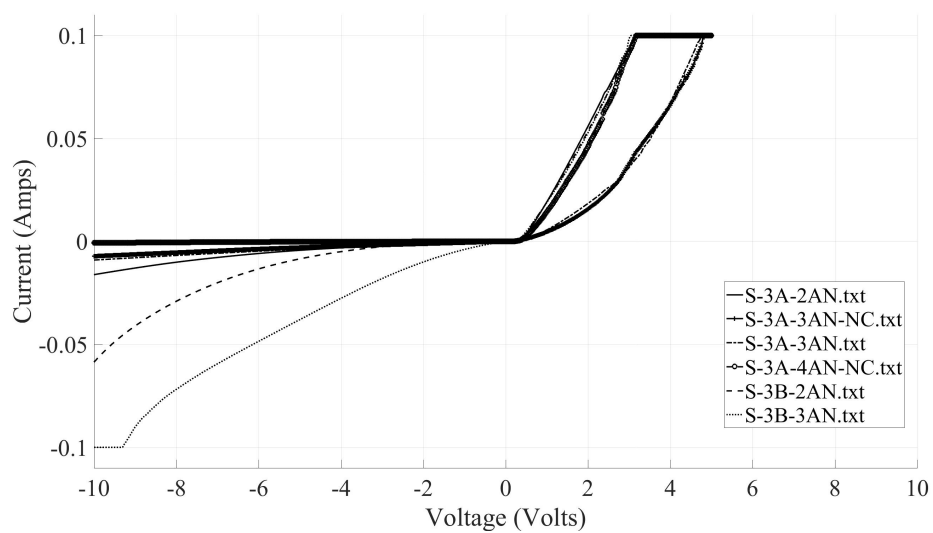


Figure F-2. Diode Test plot for Sample Set 3.

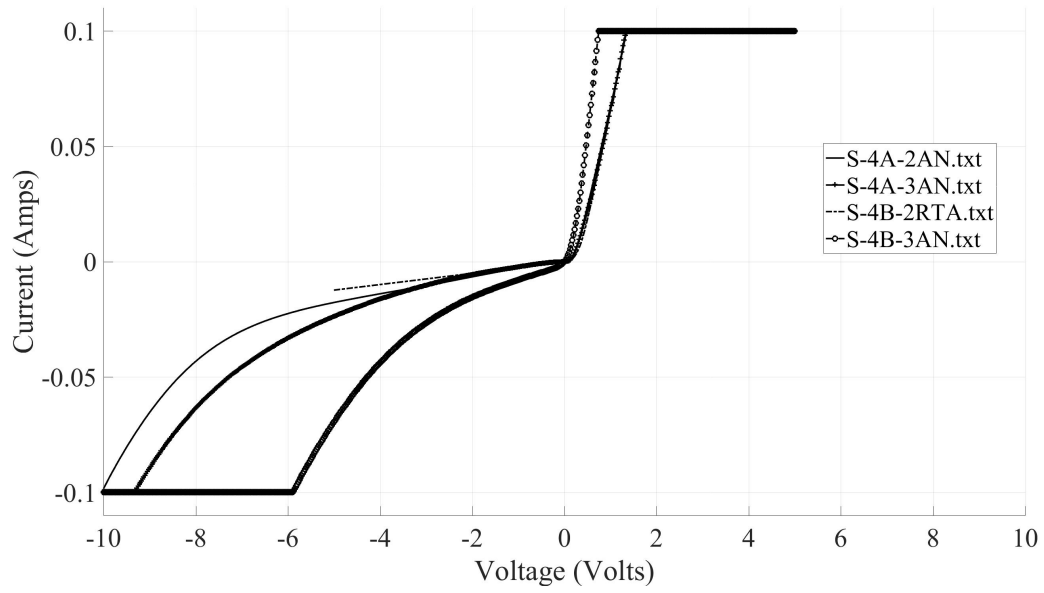


Figure F-3. Diode Test plot for Sample Set 4.

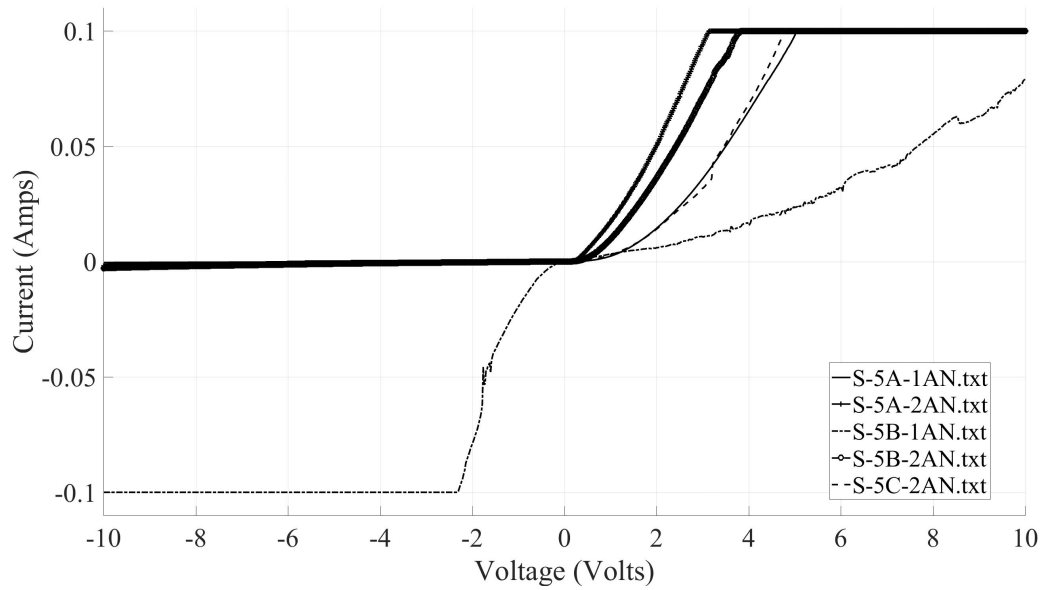


Figure F-4. Diode Test plot for Sample Set 5.

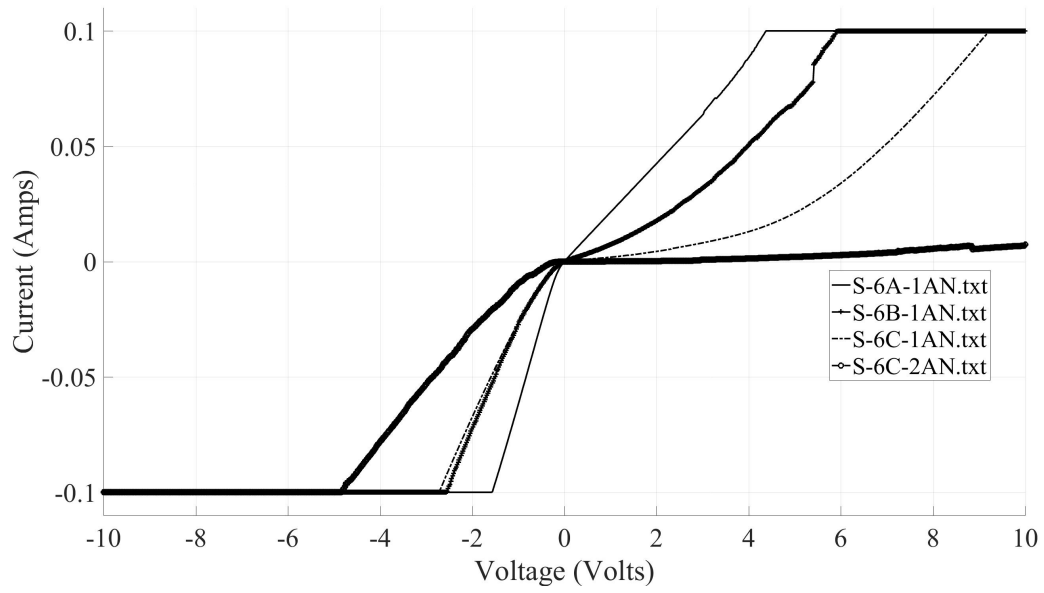


Figure F-5. Diode Test plot for Sample Set 6.

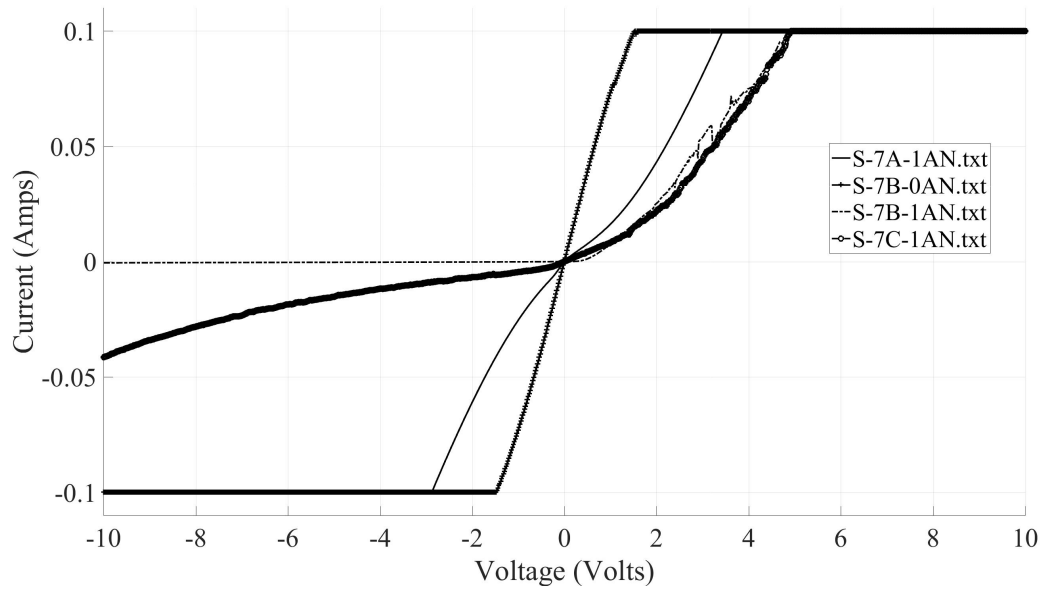


Figure F-6. Diode Test plot for Sample Set 7.

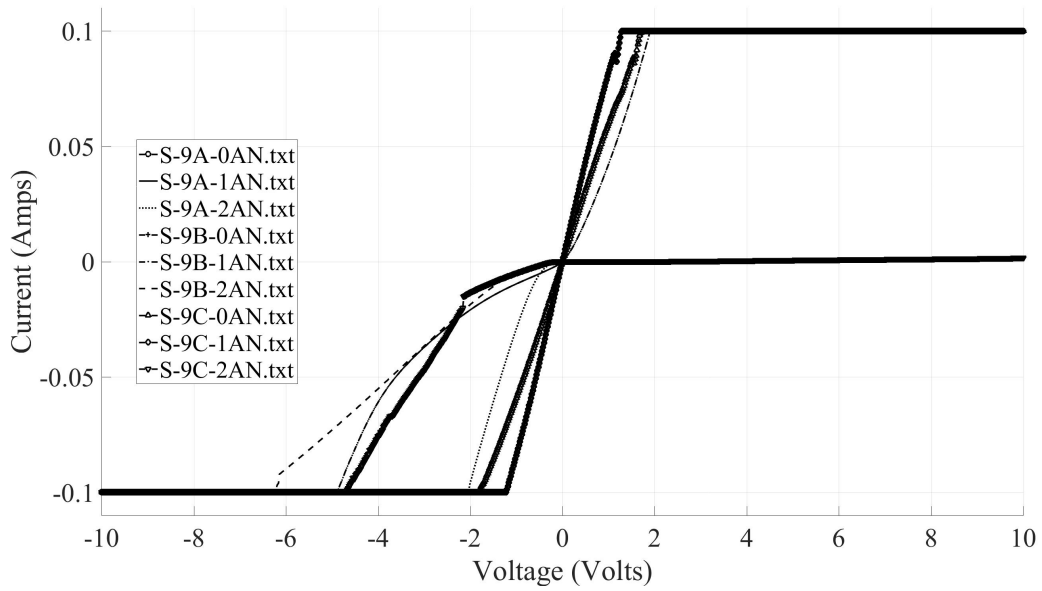


Figure F-7. Diode Test plot for Sample Set 9.

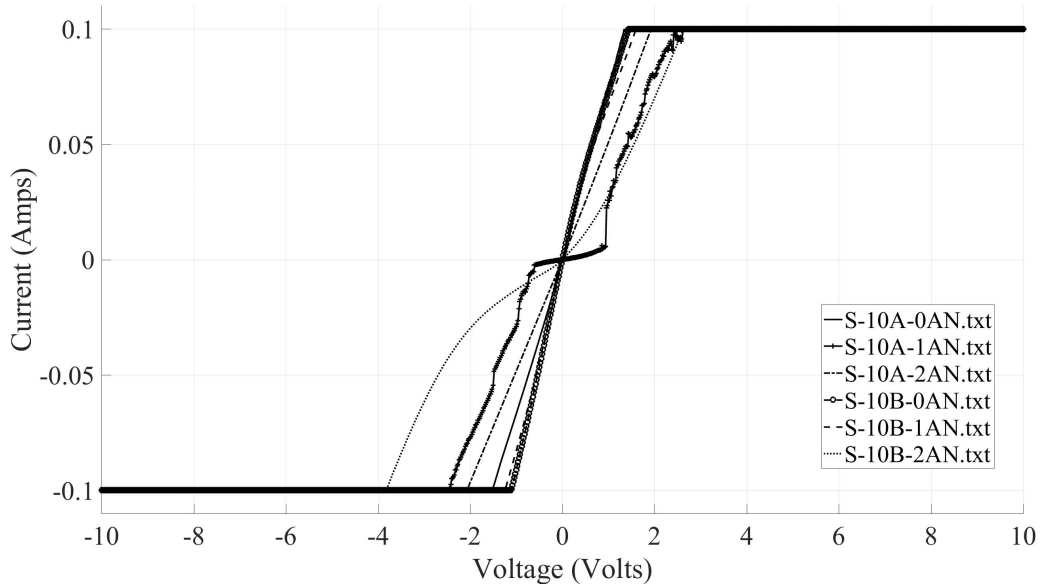


Figure F-8. Diode Test plot for Sample Set 10.

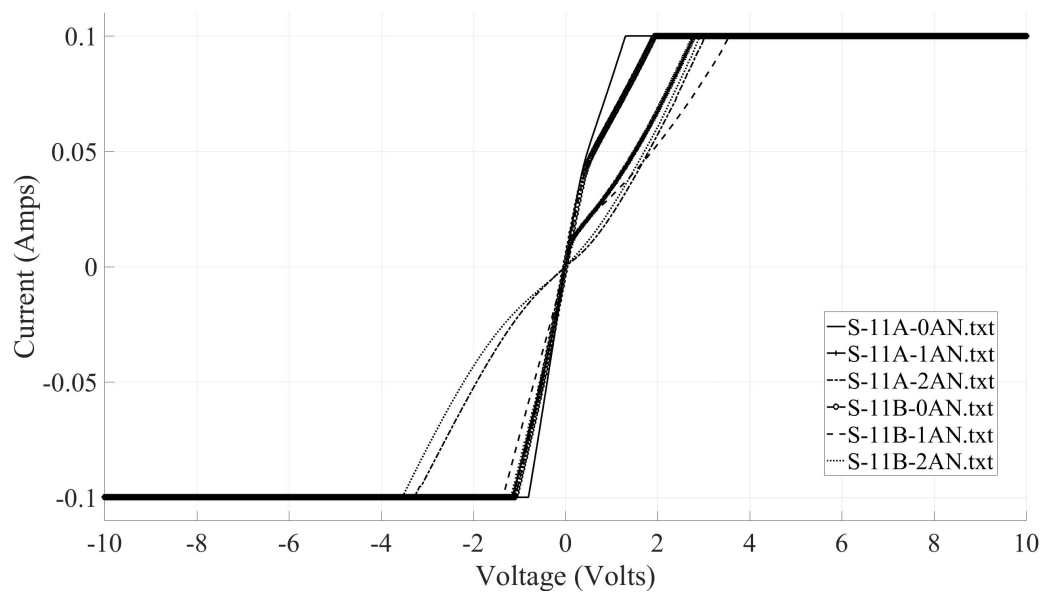


Figure F-9. Diode Test plot for Sample Set 11.

Appendix G. IV-Curve Plots

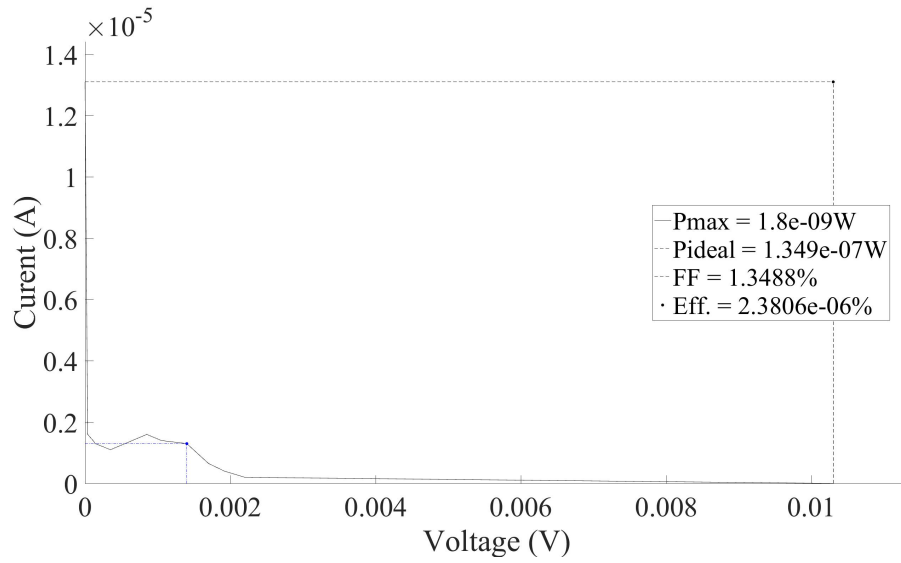


Figure G-1. IV Curve Data plot for Sample 2A.

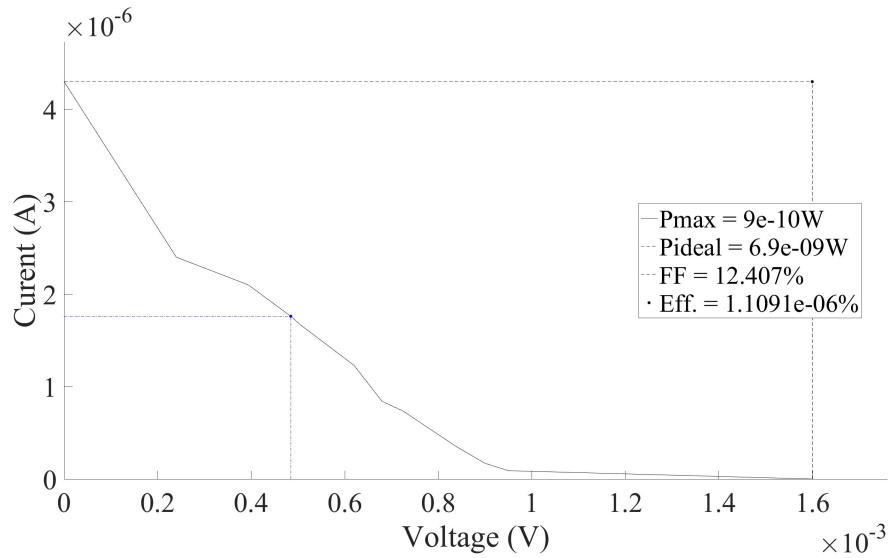


Figure G-2. IV Curve Data plot for Sample 3A.

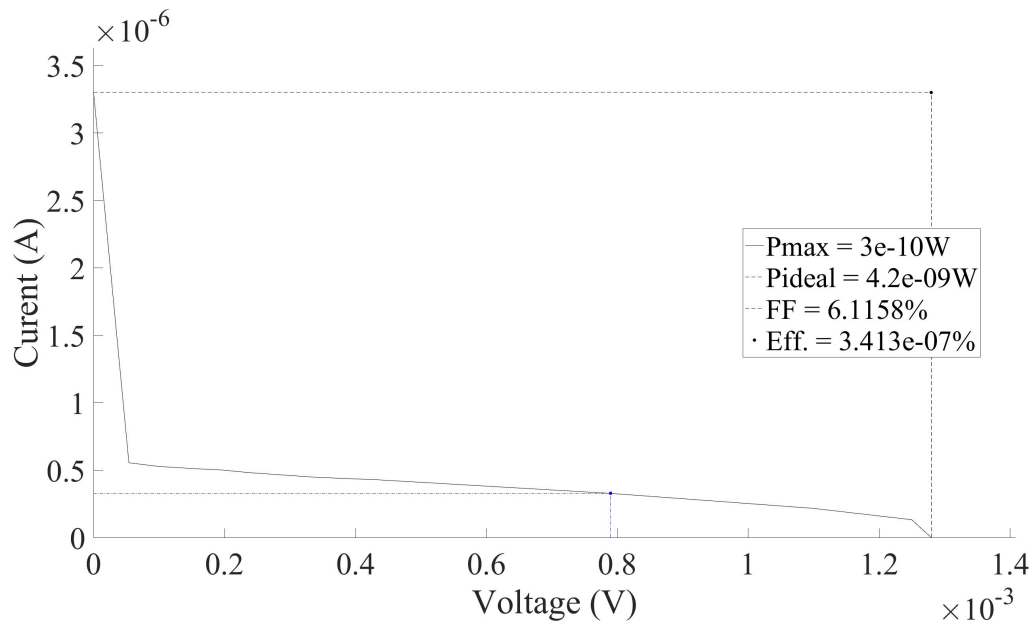


Figure G-3. IV Curve Data plot for Sample 3B.

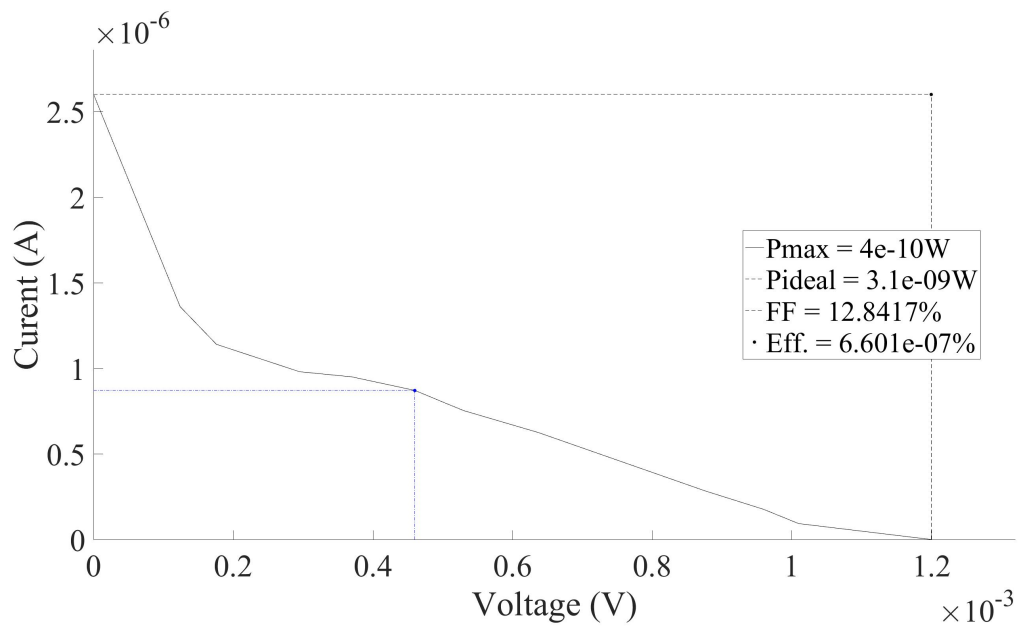


Figure G-4. IV Curve Data plot for Sample 5A.

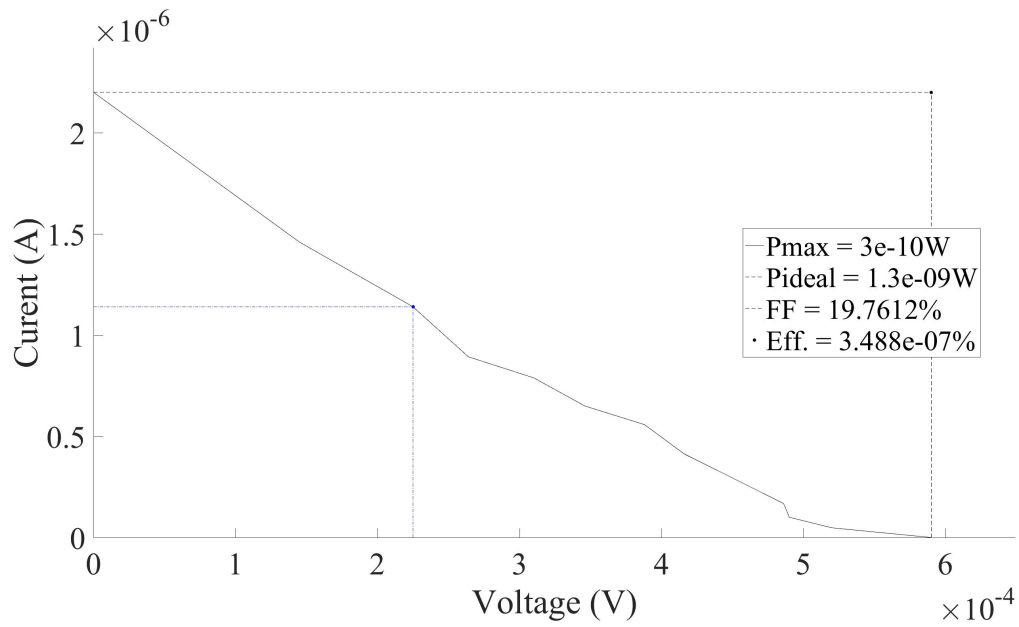


Figure G-5. IV Curve Data plot for Sample 5B.

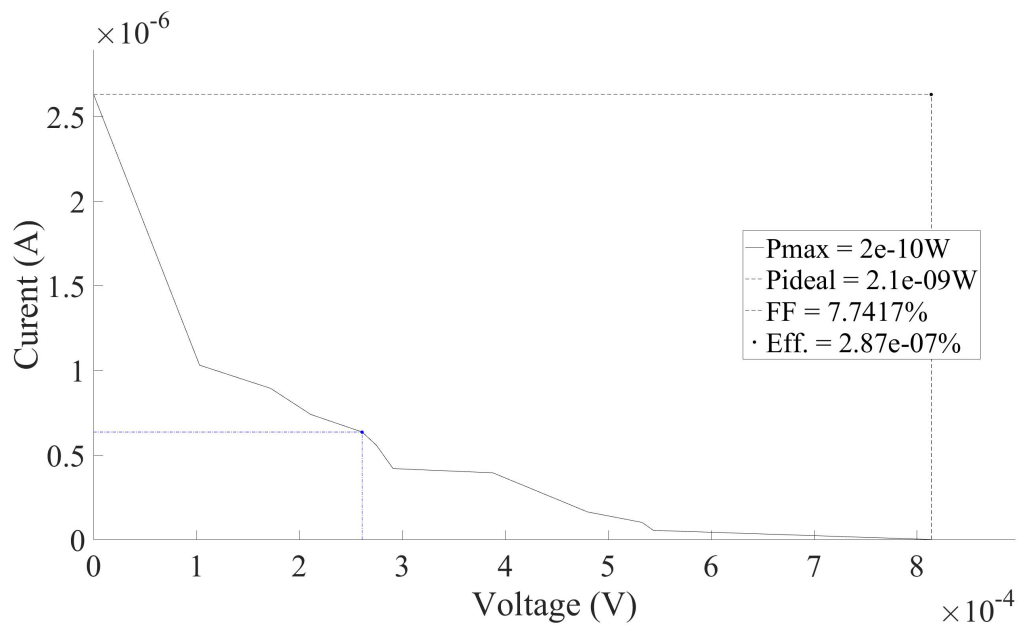


Figure G-6. IV Curve Data plot for Sample 5C.

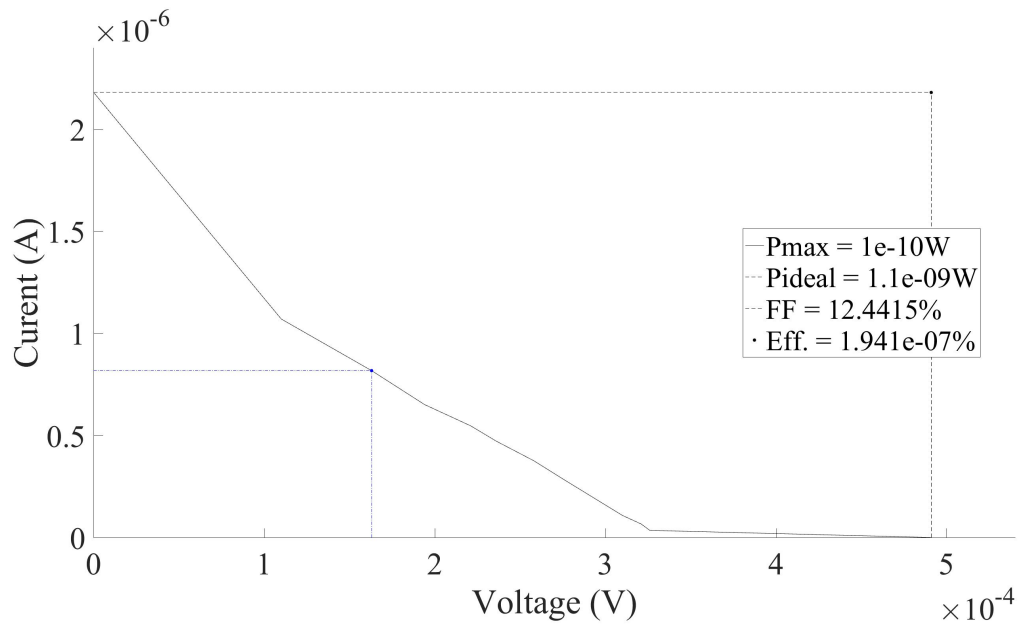


Figure G-7. IV Curve Data plot for Sample 6A.

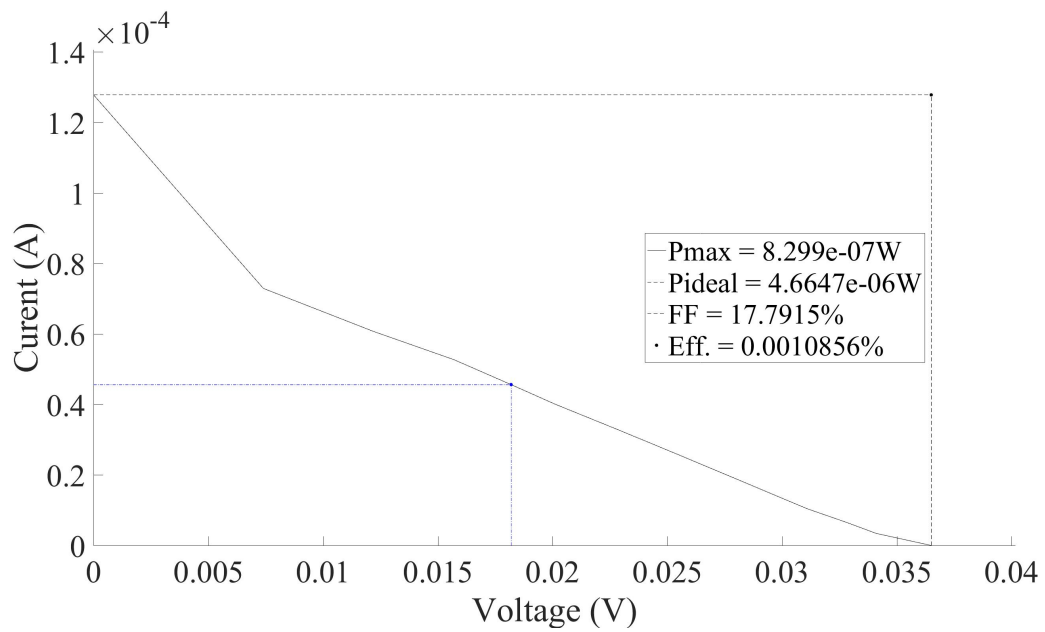


Figure G-8. IV Curve Data plot for Sample 6B.

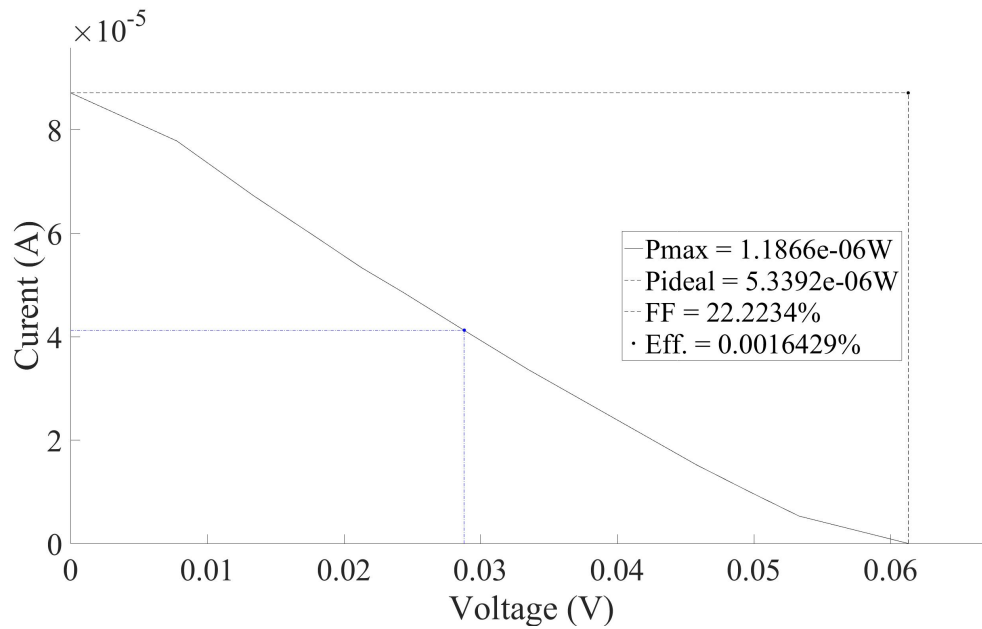


Figure G-9. IV Curve Data plot for Sample 6C.

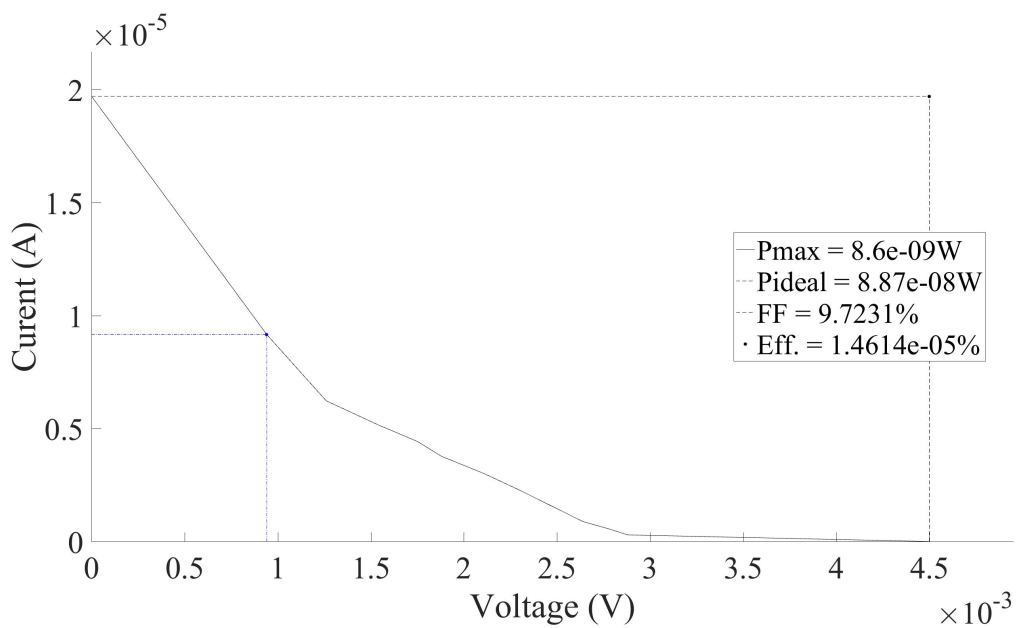


Figure G-10. IV Curve Data plot for Sample 7A.

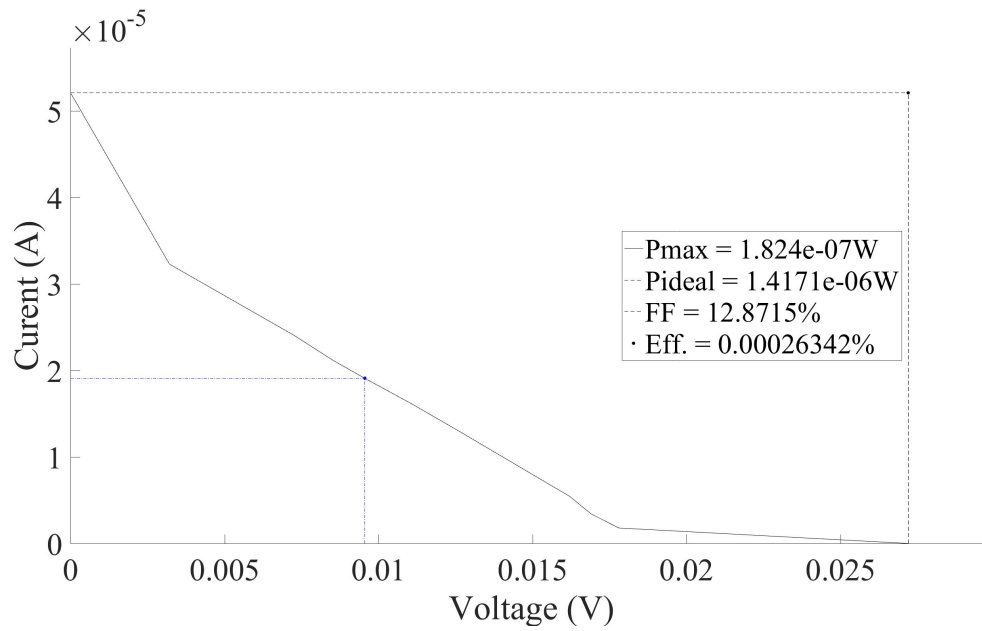


Figure G-11. IV Curve Data plot for Sample 7B.

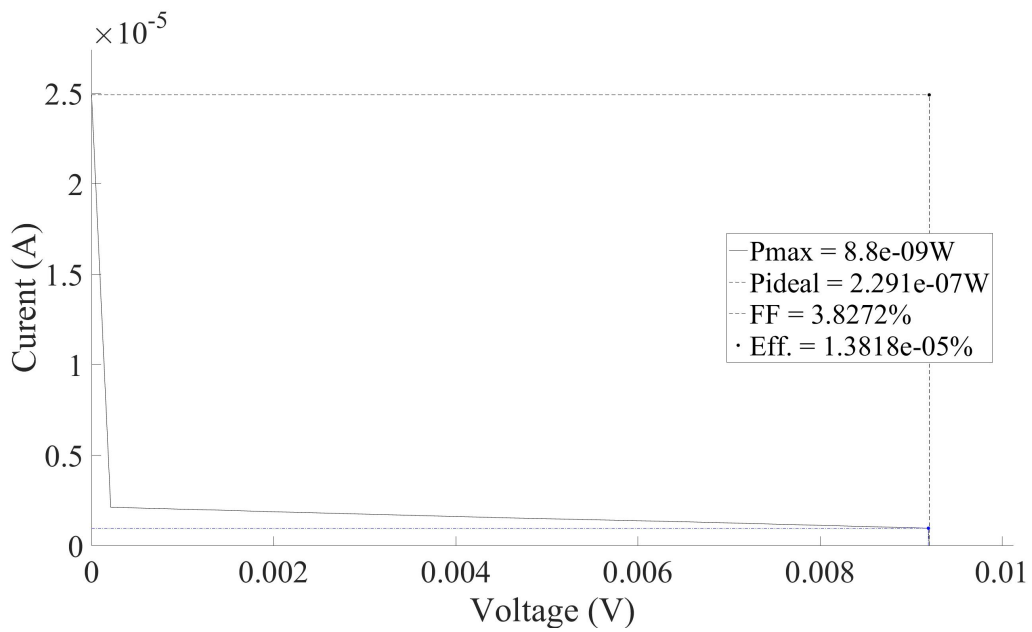


Figure G-12. IV Curve Data plot for Sample 7C.

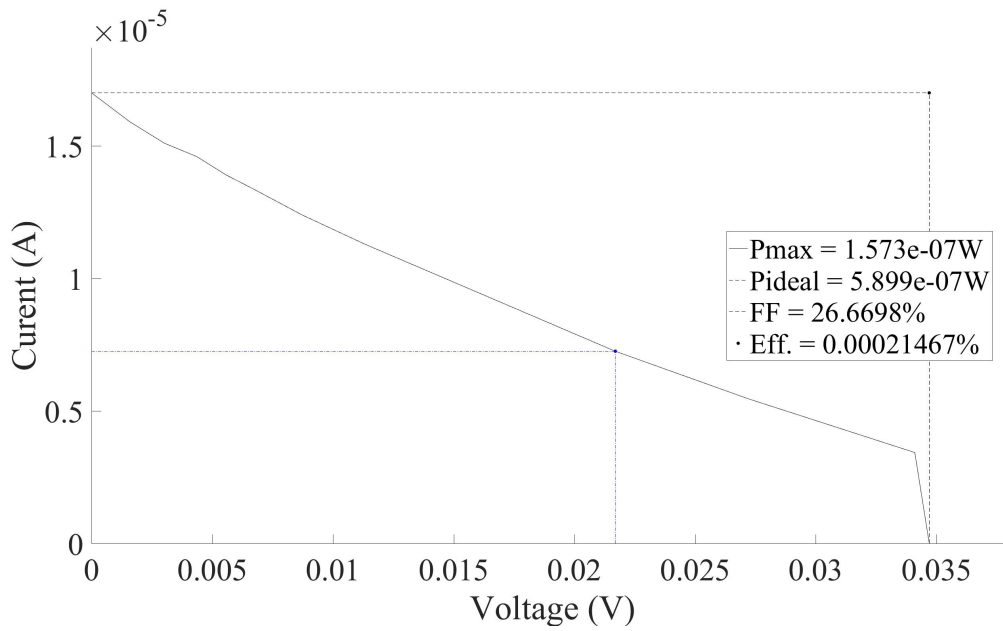


Figure G-13. IV Curve Data plot for Sample 9A.

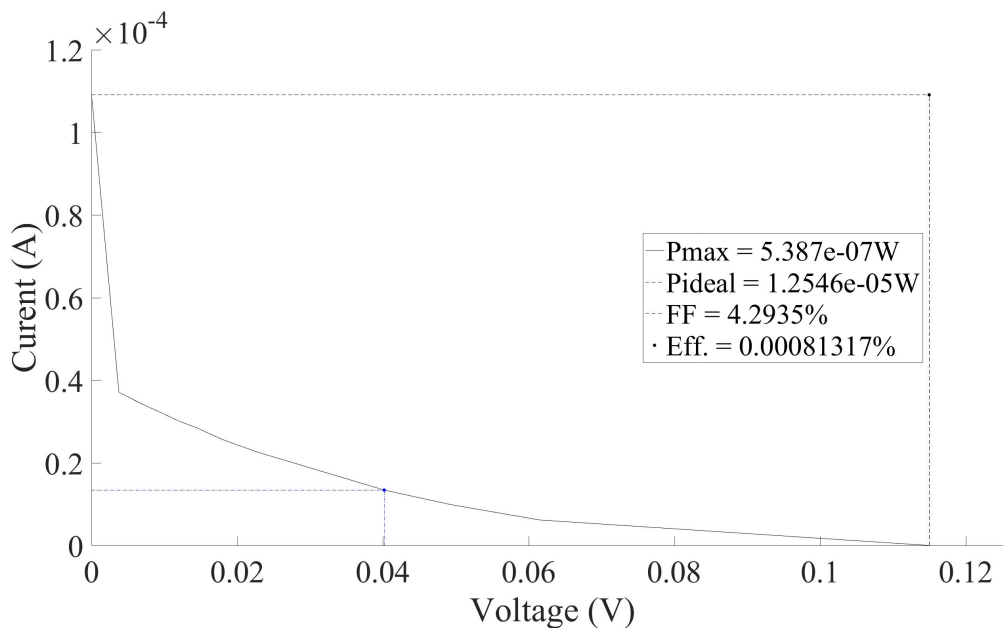


Figure G-14. IV Curve Data plot for Sample 9B.

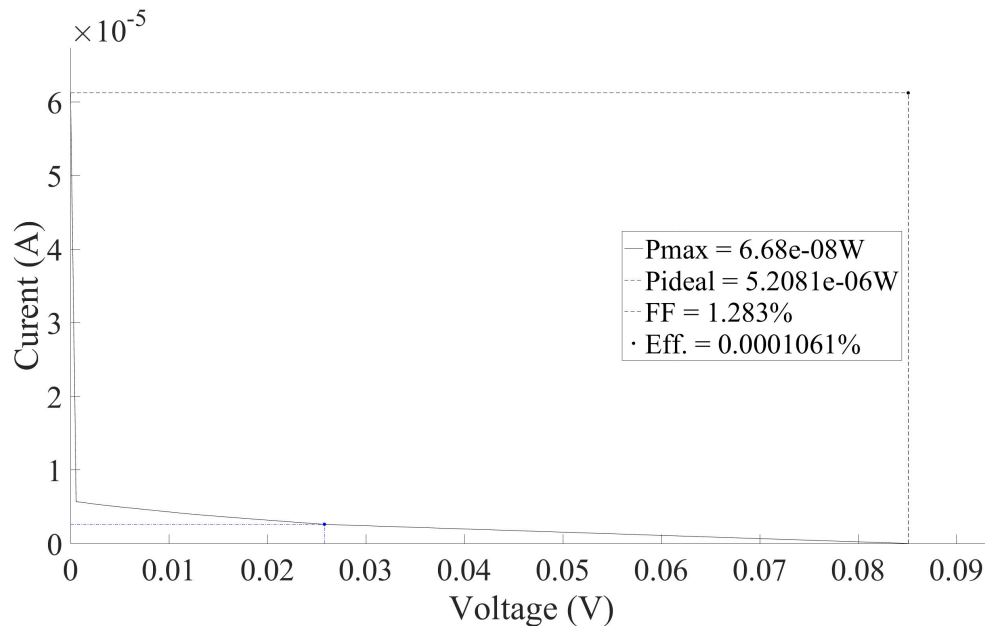


Figure G-15. IV Curve Data plot for Sample 9C.

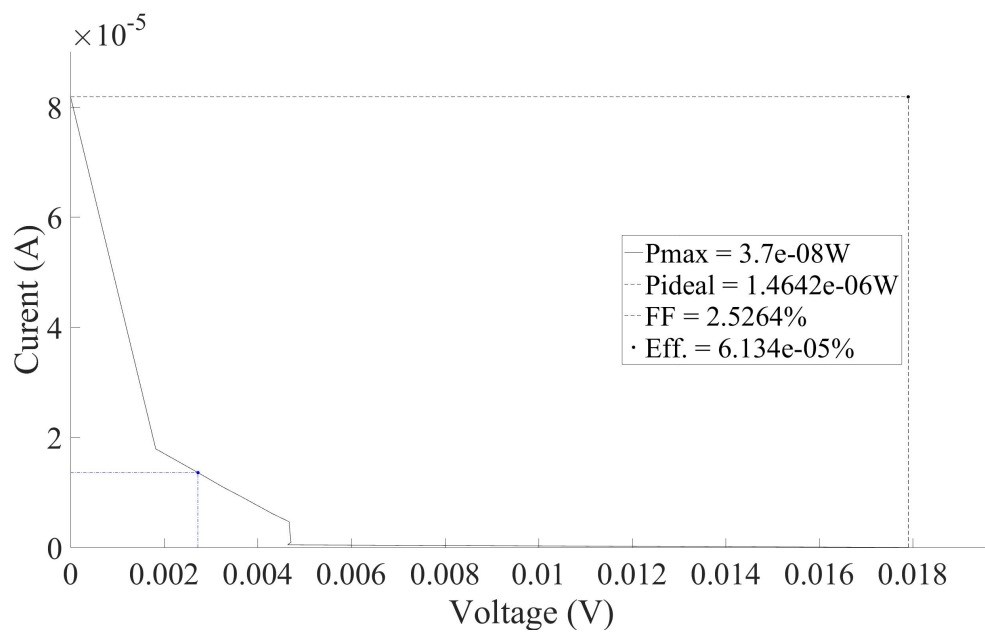


Figure G-16. IV Curve Data plot for Sample 10A.

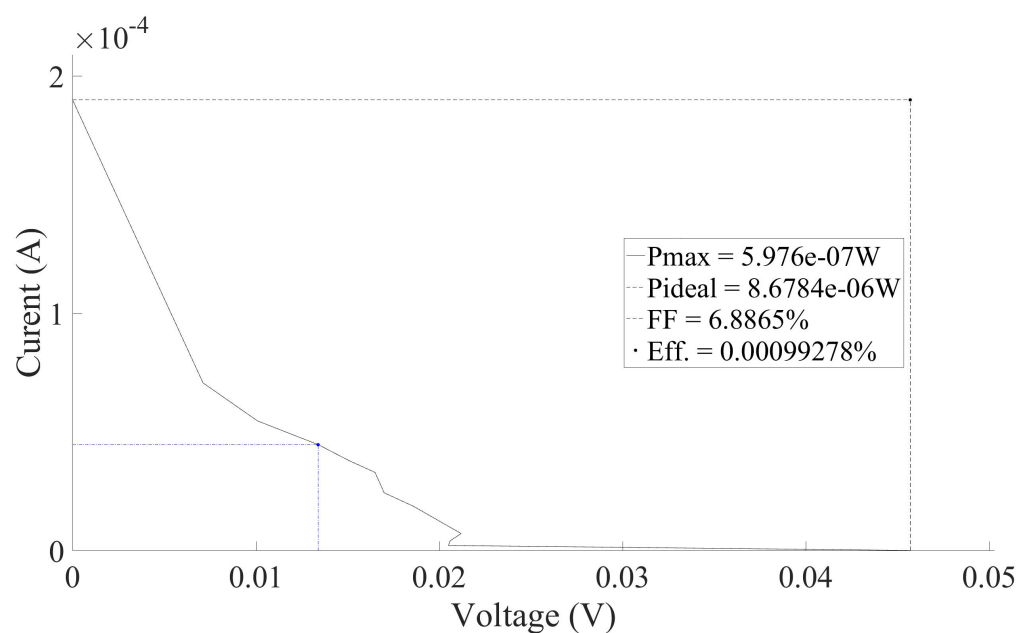


Figure G-17. IV Curve Data plot for Sample 10B.

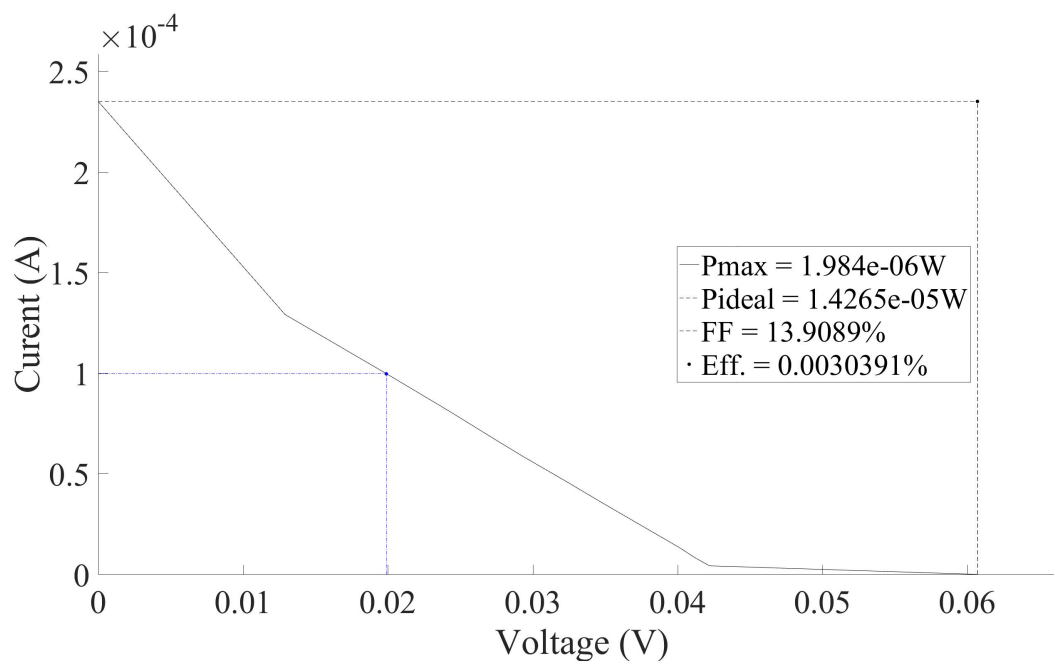


Figure G-18. IV Curve Data plot for Sample 11A.

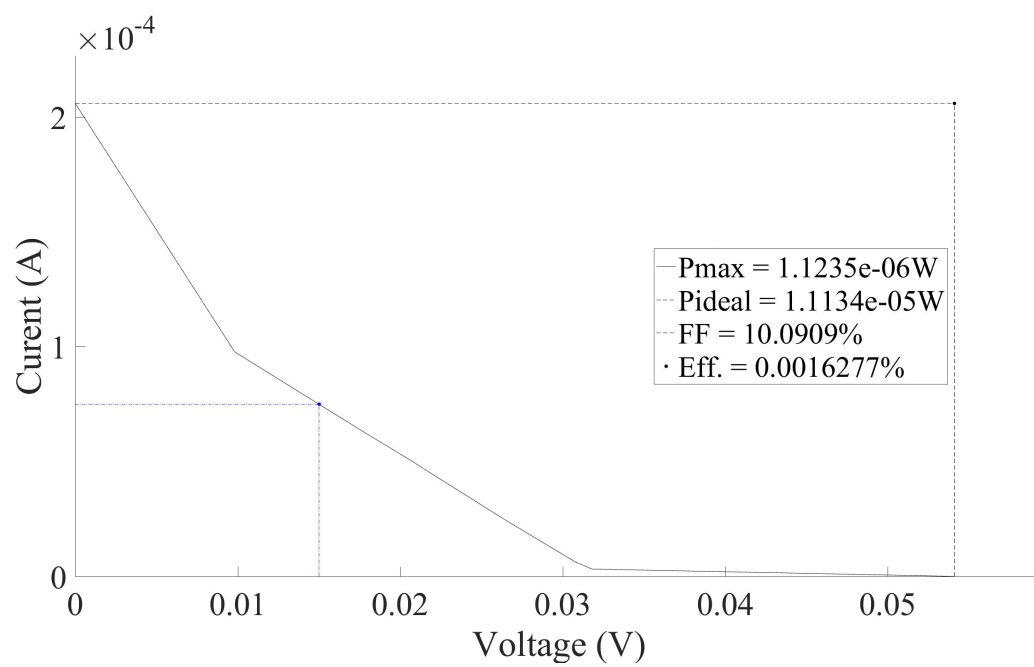


Figure G-19. IV Curve Data plot for Sample 11B.

Appendix H. Test Result Tables

Table H-1. Measured dark current (uA) and corresponding voltage (mV) of completed samples.

Sample ID	Dark Voc (mV)	Dark Isc (uA)
2A	-0.01	-0.13
3A	0.03	0.125
3B	-0.024	-0.065
5A	0.139	0.1
5B	0.033	0.07
5C	0.001	0.005
6A	0.003	0.021
6B	0.005	0.005
6C	0.018	0.006
7A	-0.003	-0.035
7B	0.013	0.002
7C	-0.02	0.01
9A	0.09	0.04
9B	0.088	0.026
9C	0.171	0.007
10A	0.003	0.02
10B	-0.001	0.026
11A	0.003	0.017
11B	0.007	0.004

Table H-2. Test results for samples placed, finger pattern facing up without anti-reflective coating, on the solar simulator calibrated at $\frac{1kW}{m^2}$.

Sample	Voc(mV)	Isc(uA)	Pmax(uW)	Efficiency(%)
2A	10.3	13.1	0.1349	0.0001%
3A	1.6	4.3	0.0069	0.0000%
3B	1.28	3.3	0.0042	0.0000%
5A	1.2	0.126	0.0002	0.0000%
5B	0.59	2.2	0.0013	0.0000%
5C	0.814	2.63	0.0021	0.0000%
6A	0.491	2.18	0.0011	0.0000%
6B	36.5	127.8	4.6647	0.0047%
6C	61.3	87.1	5.3392	0.0053%
7A	4.5	19.7	0.0887	0.0001%
7B	27.2	52.1	1.4171	0.0014%
7C	9.2	24.9	0.2291	0.0002%
9A	34.7	17	0.5899	0.0006%
9B	115	109.1	12.5465	0.0125%
9C	85.1	61.2	5.2081	0.0052%
10A	17.9	81.8	1.4642	0.0015%
10B	45.7	189.9	8.6784	0.0087%
11A	60.7	235	14.2645	0.0143%
11B	54.1	205.8	11.1338	0.0111%

Table H-3. Test results for samples placed, finger pattern facing down, on the solar simulator calibrated at $\frac{1kW}{m^2}$.

Sample	Voc(mV)	Isc(uA)	Pmax(uW)	Efficiency(%)
2A	45.8	133.4	6.110	0.0061%
3A	85.3	319.9	27.287	0.0273%
3B	68.8	328.3	22.587	0.0226%
5A	31.2	38.7	1.207	0.0012%
5B	14.2	62.9	0.893	0.0009%
5C	11.3	49.2	0.556	0.0006%
6A	12.77	53.9	0.688	0.0007%
6B	30.9	44.8	1.384	0.0014%
6C	59.5	142.9	8.503	0.0085%
7A	103.7	470	48.739	0.0487%
7B	24.7	26.7	0.659	0.0007%
7C	96.1	293	28.157	0.0282%
9A	2	0.398	0.001	0.0000%
9B	11.7	2	0.023	0.0000%
9C	5.3	2.1	0.011	0.0000%
10A	3.56	16.2	0.058	0.0001%
10B	79.6	330.9	26.340	0.0263%
11A	98.8	385	38.038	0.0380%
11B	77.6	289.2	22.442	0.0224%

Table H-4. EDAX compiled results for samples 10 and 11 atomic percentages after thermal annealing at 250°C. Germanium percentages were scaled for the approximate area of germanium-telluride present in the scanning region.

Sample 10A				Sample 11A		
Point	Atomic Pct Te	Atomic Pct Ge		Point	Atomic Pct Te	Atomic Pct Ge
1	1.22%	2.79%		1	3.44%	0.83%
2	0.90%	2.64%		2	1.45%	2.50%
3	1.14%	2.66%		3	0.38%	2.91%
4	1.11%	2.09%		4	1.72%	0.20%
5	1.14%	2.84%		5	3.30%	0.26%
6	1.22%	2.72%		6	2.23%	0.23%
7	2.05%	2.68%		7	2.38%	0.23%
8	1.81%	2.80%		8	4.63%	0.34%
9	2.16%	2.80%		9	1.40%	0.17%
10	1.51%	2.80%		10	3.28%	0.29%
11	2.17%	2.80%		11	2.15%	2.71%
12	1.65%	2.70%		12	2.41%	0.25%
13	0.97%	2.79%		13	3.15%	0.20%
14	1.09%	2.53%		14	2.71%	0.19%
15	0.44%	2.76%		15	0.72%	2.97%
16	1.72%	2.67%		16	2.47%	0.30%
Avg	1.22%	2.74%		Avg	2.40%	2.71%

Table H-5. Built in voltages for samples, calculated using the standard diode equation described in Chapter II and solar simulator test data in Table H-2 and H-3.

Sample_ID	Barrier_Finger_Down_Volts	Barrier_Fingers_Up_Volts
2A	1.145713304	1.137169236
3A	1.145704225	1.071299599
3B	1.138643372	1.066205882
5A	1.160073258	1.14151685
5B	1.11526259	1.036112678
5C	1.110473883	1.048405944
6A	1.114006817	1.026865845
6B	1.156278399	1.138410803
6C	1.153010934	1.171433703
7A	1.142570579	1.08742754
7B	1.159332746	1.147666753
7C	1.151123969	1.104973547
9A	1.139738753	1.179985681
9B	1.187794776	1.178726878
9C	1.148633425	1.18362986
10A	1.080350561	1.119505577
10B	1.142899374	1.137535585
11A	1.145717595	1.142272825
11B	1.145196195	1.141509253

Table H-6. Calculated remaining dopant concentration calculated using measured V_{oc} and Equation (13), compared to published average intrinsic concentration of $N_a \approx 8 \times 10^{20}$.

Sample_ID	Na_Up	Na_Dn	Percent Ionized
2A	2.16393E+18	8.5214E+18	1.33567%
3A	1.54654E+18	3.9161E+19	5.08842%
3B	1.52755E+18	2.071E+19	2.77968%
4A	1.55252E+18	3.1914E+19	4.18331%
4B	1.56758E+18	1.0868E+19	1.55445%
5A	1.52283E+18	4.8495E+18	0.79654%
5B	1.48739E+18	2.5156E+18	0.50037%
5C	1.50031E+18	2.2491E+18	0.46868%
6A	1.48171E+18	2.3805E+18	0.48277%
6B	5.95069E+18	4.7936E+18	1.34304%
6C	1.5503E+19	1.4462E+19	3.74566%
7A	1.72977E+18	7.9687E+19	10.17706%
7B	4.15551E+18	3.7731E+18	0.99108%
7C	1.91982E+18	5.9422E+19	7.66774%
9A	4.94402E+18	1.5706E+18	0.81433%
9B	1.23272E+20	2.2841E+18	15.69455%
9C	3.88596E+19	1.784E+18	5.08046%
10A	2.90189E+18	1.6681E+18	0.57125%
10B	8.48857E+18	3.1425E+19	4.98918%
11A	1.5148E+19	6.5951E+19	10.13739%
11B	1.17405E+19	2.909E+19	5.10376%

Table H-7. Calculated recombination rates for all samples using Equation (12) described in Chapter II and obtained test data.

Sample ID	Recombination Rate
2A2AN	3.646E+14
2A3AC	2.67365E+14
2A3AN	8.95422E+13
2A4AC	4.02301E+14
3A2AN	1.99276E+15
3A3AC	1.1625E+15
3A3AN	1.51764E+15
3A4AC	1.05419E+14
3B2AN	2.66291E+15
3B3AN	5.36193E+15
5A1AN	1.70119E+14
5A2AN	5.33254E+14
5B1AN	3.86849E+15
5B2AN	6.18156E+14
5C2AN	4.863E+14
6A1AN	8.22536E+15
6B1AN	6.18905E+15
6C1AN	3.81608E+15
6C2AN	9.2693E+14
7A1AN	7.58302E+15
7B0AN	9.92451E+15
7B1AN	3.1386E+14
7C1AN	2.85883E+15
9A0AN	1.01202E+16
9A1AN	1.01202E+16
9A2AN	5.26151E+14
9B0AN	1.01202E+16
9B1AN	6.96624E+15
9B2AN	3.29118E+14
9C0AN	9.61783E+15
9C1AN	1.01202E+16
9C2AN	4.73732E+14
10A0AN	9.90727E+15
10A1AN	7.10659E+15
10A2AN	9.2994E+15
10B0AN	1.01091E+16
10B1AN	1.00334E+16
10B2AN	7.30715E+15
11A0AN	1.03907E+16
11A1AN	9.47019E+15
11A2AN	7.62565E+15
11B0AN	1.01134E+16
11B1AN	9.05907E+15
11B2AN	7.58785E+15

Table H-8. Built in voltages for samples, calculated using the standard diode equation described in Chapter II and diode test data from Appendix D.

Sample ID	Barrier Volts
S-2A-2AN.txt	1.475797296
S-2A-3AN-NC.txt	1.451438069
S-2A-3AN.txt	1.477216244
S-2A-4AN-NC.txt	1.452781677
S-3A-2AN.txt	1.418763757
S-3A-3AN-NC.txt	1.44888711
S-3A-3AN.txt	1.442931056
S-3A-4AN-NC.txt	1.504133582
S-3B-2AN.txt	1.42536962
S-3B-3AN.txt	1.36661613
S-5A-1AN.txt	1.514311314
S-5A-2AN.txt	1.482125282
S-5B-1AN.txt	1.333571196
S-5B-2AN.txt	1.482653379
S-5C-2AN.txt	1.476837993
S-6A-1AN.txt	1.32578814
S-6B-1AN.txt	1.326948881
S-6C-1AN.txt	1.328242302
S-6C-2AN.txt	1.359931469
S-7A-1AN.txt	1.330224514
S-7B-0AN.txt	1.310966849
S-7B-1AN.txt	1.498354435
S-7C-1AN.txt	1.405324459
S-9A-0AN.txt	1.314587474
S-9A-1AN.txt	1.314587474
S-9A-2AN.txt	1.323723912
S-9B-0AN.txt	1.314587474
S-9B-1AN.txt	1.352861166
S-9B-2AN.txt	1.3713485
S-9C-0AN.txt	1.32491076
S-9C-1AN.txt	1.314587474
S-9C-2AN.txt	1.373908162
S-10A-0AN.txt	1.308577776
S-10A-1AN.txt	1.318729997
S-10A-2AN.txt	1.319545388
S-10B-0AN.txt	1.316620588
S-10B-1AN.txt	1.314213037
S-10B-2AN.txt	1.35044384
S-11A-0AN.txt	1.319999933
S-11A-1AN.txt	1.315961123
S-11A-2AN.txt	1.328831792
S-11B-0AN.txt	1.317093492
S-11B-1AN.txt	1.311025262
S-11B-2AN.txt	1.329679251

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Vita

Lt Jones began his military career in 1999 when he enlisted shortly after graduating high school in El Paso, TX. His first assignment was working in aircraft maintenance on the A-10 Warthog at Davis-Monthan AFB in Arizona. From there he transitioned to the 517th Airlift squadron at Elmendorf AFB, Alaska from which he had the opportunity to support Operation Enduring Freedom in 2004. He obtained a Bachelor of Science degree at the University of New Mexico in 2013 while serving at Kirtland AFB. The same year, he earned his commission from the U.S. Air Force Officer Training School. Following this, his first commissioned assignment was writing mission planning software at the 76th Software Maintenance Group at Tinker AFB, Oklahoma. Lt Jones' decorations consist of: Air Force Commendation Medal, Air Force Achievement Medal, AF Outstanding Unit Award, National Defense Service Medal, Global War on Terrorism Service Medal, Nuclear Deterrence Operations Service Medal, AF Longevity Service Ribbon, USAF NCO PME Graduate Ribbon, Small Arms Marksmanship Ribbon and AF Training Ribbon.

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14. ABSTRACT In the solar industry today many new endeavors rely on improving efficiency on existing solar technologies such as silicon and gallium arsenide based solar cells. Other new technologies tend to lean towards cadmium or organic based devices in an attempt to produce more effective, less costly solar devices. While this is good for business and growth, the underlying problem of improving efficiency will not be solved by staying in a low cost box of a handful of choices. This research is focused outside this material box by looking into improving the hybrid multi-junction silicon germanium (HMJ-SiGe) solar cell structure, a germanium based solar cell device. An antimony doped germanium substrate is used in conjunction with germanium telluride, in an approximate 1:1 ratio in order to produce a functional solar cell device. Using standard processing techniques already in use in the commercial industry, samples are created and tested using solar simulator, spectroscopic equipment and standard electronics testing equipment. Layering germanium telluride on top of a doped germanium sample, followed by contacts and an anti-reflective layer of silicon nitride allowed for a functional solar cell producing 103.7mV and 470uA developing a 0.049% efficient device. These results show that a device is feasible, however more research into improving efficiency and lowering costs are required before it can be adapted for use in other device structures.						
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